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Spatial variability in response of deltaic baldcypress forests to hydrology and climate

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SPATIAL VARIABILITY IN RESPONSE OF DELTAIC BALDCYPRESS FORESTS TO HYDROLOGY AND CLIMATE

A Thesis

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ABSTRACT

Changing hydrology and climate have significantly altered ecologically significant cypress-tupelo forests in the deltaic plain of the Mississippi River. Though local responses of these swamps to hydrology are relatively well understood, broad-scale evaluation of ecological response differences of deltaic wetland forests has been limited by the lack of site-specific coupled hydrologic and ecological data. Baldcypress tree-rings from twenty-two sites were used to examine the responses of coastal swamp forests throughout the deltaic plain to environmental variables. The responses of these forests to environmental variables varied spatially; however, broad-scale measures of deltaic hydrology were more correlated with tree radial growth than were climatic variables. A strong relationship between coastal water levels and river stage suggests that river stage often controls coastal water levels near the coast, so that even sites not locally hydrologically connected to the river experience broad-scale effects of annual variability in Mississippi river stage. Thus, even though the river is leveed, river stage appears to have significant impacts on forest productivity through linkages with coastal water levels.

INTRODUCTION

Changing climate and hydrology have significantly affected wetland community composition and ecosystem processes around the world (Lloyd and Fastie, 2002). Forest ecosystems respond to historic and recent climatic and hydrologic variability. According to the report of Intergovernmental Panel on Climate Change (IPCC: Solomon et al. 2007), atmospheric temperature significantly increased over the period from 1850-1899 to 2001-2005. There are several predictions about the significant rise of global temperature over time, which will result in substantial sea level rise by the end of 21st century (Solomon et al., 2007; Rahmstorf, 2007; Holgate et al., 2007). Hoffman et al. (1983) predicted that the Atlantic and Gulf Coasts of United States will face a sea level rise of 18-24 cm more than the global average of 144-217 cm by 2100. They have also stated that this rise in average Gulf Coast sea level will result in disastrous events such as erosion, flooding, and saltwater intrusion in coastal zones that will pose serious economic and ecological problems. The predicted changes in climate and hydrology will likely significantly influence forest ecosystems and their productivity. Hydrological changes have already taken place in Louisiana, where actual sea level rise is exacerbated by increasing subsidence in coastal areas (Day et al., 1995).

The coastal wetland forests in the deltaic plain of the Mississippi River represent the premier wetland forests of the state, most of which are second-growth (Conner and Toliver, 1990) that naturally regenerated after logging over the past 80 to 120 years (Norgress, 1947; Mancil, 1972). The dominant species in the coastal wetland forest of south Louisiana are baldcypress (*Taxodium distichum*) and water tupelo (*Nyssa aquatic*a). Coastal cypress-tupelo forest stands that make up the largest area of coastal wetland forest have experienced a great deal of climatic and hydrologic variability (Chambers et al., 2005).

The coastal wetland forest ecosystems provide a number of ecosystem services such as hurricane protection, water quality improvement, timber production, aesthetic value, floodwater storage, coastal storm surge protection, recharge of aquifers, carbon storage, erosion control, nutrient cycling, wildlife habitat, and others (Reams and Van Deusen, 1998; Chambers et al., 2005; Mitsch and Gosselink, 2007). Understanding responses of these coastal wetland forests to changing climate and hydrology by sites and in an overall regional scale is therefore important. Climatic and hydrologic changes might result in shifts in community composition and ecosystem processes and may endanger the ecosystem functions and services provided by these forests.

Many factors of climate and hydrology affect the productivity of coastal wetland forests. Large scale hydrologic and geomorphic alterations such as land loss, subsidence, sea-level rise, levee construction, and faulting, plus many small scale factors such as depth and duration of flooding, salt water intrusion, nutrient and sediment deprivation, herbivory, invasive species, etc. have affected the health of the coastal wetland forest (Hatton et al., 1983; Pezeshki et al., 1990; Saucier, 1994; Chambers et al., 2005). The productivity in the deltaic baldcypress forests is mostly governed by hydrology (Conner, 1994; Young et al., 1995) and its interaction with other components of ecosystems such as climate and stand history (Keim and Amos, in press). The decline in productivity of coastal forests is due to the extensive hydrological changes in this system because of coastal erosion, sea-level rise, and subsidence (Conner and Brody, 1989; Conner and Toliver, 1990; Day et al., 2000).

The hydrology, salinity, and biogeochemistry vary among the three interdistributary basins (Atchafalaya, Lake Verret, and Lake Pontchartrain). In the Atchafalaya Basin, sites receive sediment and nutrients during spring from the riverine inflow from the Atchafalaya River. In contrast, the sites in the Lake Verret basin do not receive any riverine inflow and sediment (Madden, et al., 1988). Therefore, precipitation, upland runoff (Madden et al., 1988), and flooding due to subsidence and backwater flooding from the Atchafalaya River are the sources for water inflow into the Lake Verret sites (Conner and Brody, 1989). In the Lake Pontchartrain Basin (LaBranche wetlands), the wetlands have low salinity (Cramer et al., 1981) and consist of brackish, saline marsh and shallow ponds (Baumans et al., 1997). These sites are excluded from receiving riverine input and sediments from the Mississippi River (Pierce, 1985). Moreover, the LaBranche wetlands usually get flooded during the period of high tide via openings at Lake Pontchartrain (Boshart, 2004). In general, the local hydrology varies considerably across the sites.

Tree rings record information related to climate signals (Fritts, 1976; Briffa et al., 1992; Stahle et al., 1985; Anderson et al., 1995) and hydrology (Young et al., 1995; Cleaveland, 2000); but, tree rings are often not adequately used to understand either (Stahle and Cleaveland, 1992; Young et al., 1995). The tree rings can be used to investigate various past climatic and hydrologic phenomena, such as fire and forest disturbance history and, geomorphologic and archeological events. There have been several dendrochronological studies in the southeastern US that have made some inference about the relationships among tree radial growth, climate, and hydrology. Often baldcypress is used because it is one of the few species with such long tree-ring records. The baldcypress is a cross-datable tree species and therefore appropriate for use in dendrochronological studies (Stahle et al., 1985; Speer, 2010). Baldcypress tree rings have been used to understand natural phenomena such as precipitation (Stahle and Cleaveland, 1992; Stahle and Cleaveland, 1994); drought (Stahle et al., 1988); El Nino/Southern Oscillation (Stahle and Cleaveland, 1993); sunshine duration (Stahle et al., 1991); summer stream flow (Cleaveland, 2000); and tectonic activity (Stahle et al., 1992). Baldcypress rings have also been used for analysis of growth, flooding influence, and productivity (Young et al., 1993; Young et al., 1995; Hesse et al., 1998; Amos, 2006).

Despite these myriad studies related to climate and hydrology that have used baldcypress tree-rings in the southern US, there has been no study to explore whether relationships between growth and environmental variables are consistent in space throughout the deltaic plain of the Mississippi River. Moreover, previous studies have documented the local responses of cypress-tupelo forests in the deltaic plain of the Mississippi River to changing climate and hydrology. These site-specific studies only concentrate on localized effects of the climate and hydrology on tree radial growth (for example, Amos, 2006). Forecasting ecological response of the deltaic wetland forests to hydrology, as a whole, is needed to understand the response of wetland forests to changing hydrology in the deltaic region of the Mississippi River. Therefore, tree-ring analysis might be a promising method to assess historical trends and make predictions about future changes in coastal wetland forests. Simultaneously, a regional analysis of tree rings may provide a new understanding of the spatial variability of processes driving our deltaic ecosystem that could then be used to develop restoration plans.

Objectives

The general objective of this study is to understand the spatial variability of response of coastal swamp forests of the deltaic plain of the Mississippi River in Louisiana to environmental factors.

Specifically, this study attempts to (i) evaluate whether hydrology is a potential driving factor in radial growth of baldcypress swamp forests as found in previous studies, and (ii) investigate the relationships among radial growth of coastal forests, climatic, and hydrologic variables in space and determine how those factors are operating across the deltaic plain.

General Dendrochronological Methods

Field Sampling: Field sampling differs depending on the types of studies. For example, sampling strategies for climate studies differ from those for fire history. The general procedure for collection of samples in dendroclimatology is described here. Mostly dominant and codominant trees, which are sensitive to climate and the responses are less affected by other stand attributes are sampled. A standard tree increment borer is most often used to collect sample, but occasionally a 24-volt ½-inch cordless drill is combined with a Haglof increment borer chuck normally used to sample boards. The drill system can only be used for medium-sized trees as the maximum length for borers specified for use of the drill is 8 inches. All trees are cored at diameter at breast height (dbh) unless buttressed or otherwise distorted at this position. If buttressed, trees are most commonly cored either at 18 inches above the butt-swell or cored at 10 feet for consistency (Parresol and Hotvedt, 1990). For most trees, two cores per tree are taken to allow for examination of within-tree radial growth variation and to sufficiently enable for accurate cross-dating of chronology. Generally, cores are taken at right angles to each other; but, for leaning trees, samples come from opposite sides of the tree bole and are taken perpendicular to the lean to avoid tension or compression wood effects. Extracted cores are placed in labeled plastic straws with holes to allow the cores to air-dry; and the straw ends are sealed.

Laboratory Methods: In the lab, the cores are dried in the oven at 60°C for about 24 hours (Speer, 2010), mounted on grooved wooden mounts, and then sanded using standard dendrochronological methods and finally prepared for measurement **(**Stokes and Smiley, 1968).

The samples then are cross-dated using skeleton plot methods (Stokes and Smiley, 1968) or visual match-mismatch methods (Phipps, 1985) based on presence of marker rings. Cross-dating is assigning the exact calendar year to each annual ring (Douglass, 1941a, b). The convention described by Stokes and Smiley (1968) is generally followed to count and mark all the cores by method of dotting. The marker rings are narrow rings in trees occurring in most trees (Speer, 2010) that are produced under limiting environmental conditions.

In addition to cross-dating, ring widths are measured and recorded nearest to 0.01mm using Velmex measuring stage (model A60, Bloomfield, New York) and WinWedge software. A computer program COFECHA is used to verify cross-dating and accuracy of measurements (Holmes, 1983; Grissino-Mayer, 2001). COFECHA is a computer program developed by Richard L. Holmes in 1982, which uses segmented time series correlation to verify the cross-dating and measurement accuracy of tree-ring chronology (Grissino-Mayer, 2001).

A regional curve standardization (RCS) method is followed to preserve low frequency variability in tree ring chronologies (Briffa et al., 1992; Esper et al., 2003; Bunn et al., 2004). The RCS chronologies are developed aligning tree ring series by their cambial age (Esper et al., 2002; Esper et al., 2003). The tree-ring data are age-normalized (detrended) using ratio option, and/or prewhitened to remove serial autocorrelation and modeled for climate. ARSTAN, a computer program developed by Dr. Edward R. Cook at the Tree-Ring Laboratory, Lamont-Doherty Earth Observatory of the Columbia University, Palisades, New York, can also be used to remove age-related growth trend and other unwanted noise from tree-ring series (Cook, 1985; Cook & Holmes, 1986). Either linear regression, negative exponential curve fitting or cubic smoothing splines can be applied as detrending techniques based on the growth trend of trees.

METHODS AND MATERIALS

Tree-ring Data Source

Tree-ring data previously collected from 22 sites in Louisiana (Figure 1, Table 1, Appendix A) were used in this study. Raw annual tree ring data were supplied by the School of Renewable Natural Resources Tree-ring Lab and were primarily collected by Dr. Richard Keim of the LSU Agricultural Center and colleagues (Appendices A, B). The raw annual tree ring measurements were cross-dated, verified, and measured using standard dendrochronological methods (Stokes and Smiley, 1968; Grissino-Mayer, 2001) by various persons (Appendices A, B).

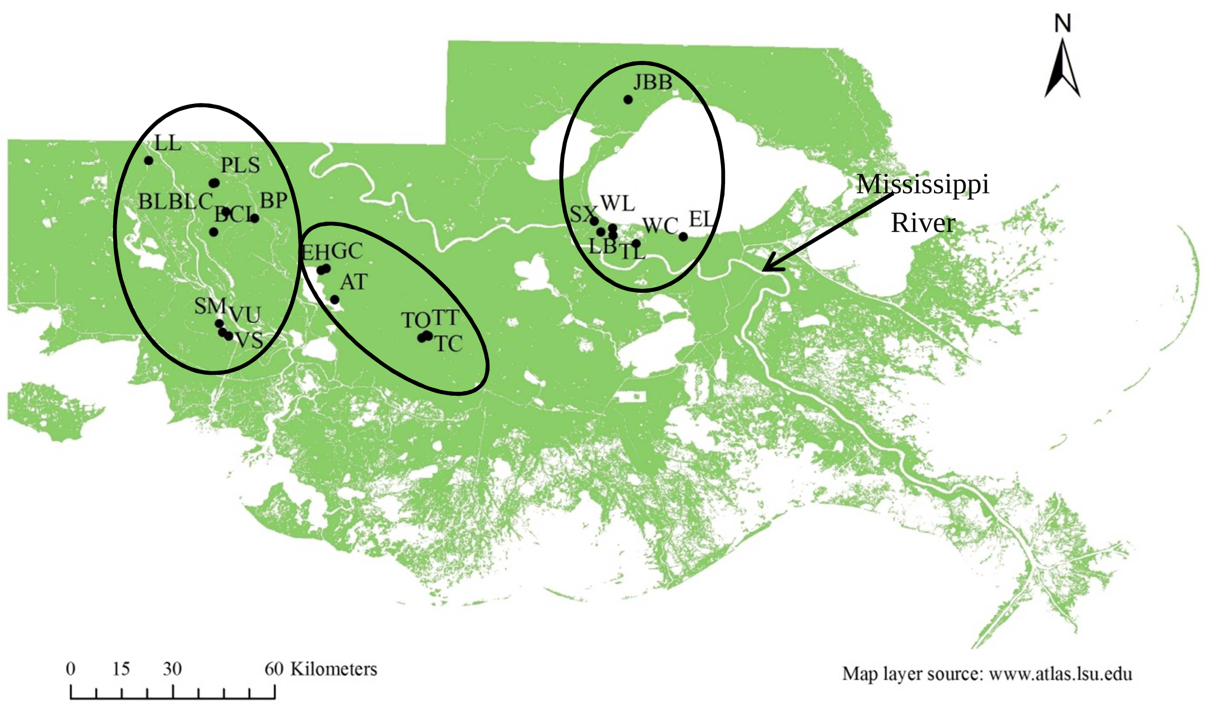

Figure 1: Locations of tree-core collection sites in south Louisiana. The far left ellipse represents sites within the “Atchafalaya Basin”, the middle ellipse represents the“Lake Verret Basin” and the far right ellipse represents the “Lake Pontchartrain Basin” sites.

Table 1: Summary statistics for site chronologies.

Sites[1]	Number of dated trees	Series range	Chronology length (yrs.)	Interseries Correlation[2]	Mean Sensitivity[3]
AT	10	1895-2004	110	0.574	0.501
BBL	9	1887-2006	120	0.558	0.583
BCL	8	1894-2006	112	0.624	0.621
BLBLC	14	1825-2007	183	0.649	0.532
BP	7	1918-2005	88	0.520	0.424
EH	10	1887-2005	119	0.547	0.602
EL	10	1888-2008	121	0.585	0.548
GC	10	1890-2005	116	0.542	0.495
JBB	17	1804-2006	203	0.544	0.387
LB	14	1888-2008	121	0.589	0.581
LL	9	1853-2006	154	0.493	0.443
PLS	13	1797-2007	211	0.679	0.513
SM	10	1885-2005	121	0.541	0.550
SX	10	1887-2008	122	0.544	0.573
TC	10	1883-2005	123	0.589	0.515
TL	10	1888-2008	121	0.461	0.473
TO	10	1840-2005	166	0.671	0.500
TT	11	1878-2005	128	0.527	0.505
VU	11	1916-2004	89	0.638	0.474
VS	14	1877-2005	129	0.529	0.543
WC	10	1831-2008	178	0.548	0.502
WL	6	1885-2008	124	0.551	0.536

[1] **AT**=Attakapas; **BCL**=Bayou Cowan Low-flow; **BP**=Bayou Pigeon; **BBL**=Bee Bayou Low-flow; **BLBLC**=Berry Lake; **EH**=Elm Hall; **EL**= Bonnet Carré East Levee; **GC**=Godchaux Canal; **JBB**=Joyce WMA Black Bayou; **LB**=LaBranche; **LL**=Long Lake; **PLS**=Pierce Lake South; **SM**= Six Mile North; **SX**= Bonnet Carré Suxion Canal; **TC**= Thibodaux Control; **TL**= Bayou Traverse and LaBranche; **TO**= Thibodaux Outflow ; **TT**=Thibodaux Treatment; **VU**= Verdunville; **VS**= Verdunville South / Grayhorse; **WC**= LaBranche Walker Canal; **WL**= LaBranche West Levee

[2] Interseries correlation is an average correlation coefficient between each tree-ring series and a master chronology from all other series (Holmes, 1983; Grissino-Mayer, 2001).

[3] Mean sensitivity is the measure of relative change of ring-width from one year to next in a series (Holmes, 1983; Grissino-Mayer, 2001).

Tree-ring Width Modeling

Each annual tree-ring width is a function of various factors affecting growth. The tree-ring widths were modeled following Cook (1987) as

$$R_t = f\,(a_t, c_t, h_t, \varepsilon) \qquad \text{Eq. (1),}$$

where, R_t is observed ring width of a tree-ring series in year t; a_t is the effect of age; c_t is the effect of variations in climate; h_t is the effect of variations in water level; and ε is error not accounted for in other terms, including stand disturbance.

Regional Curve Standardization for Estimating Biological Growth Trend

Tree-ring standardization is a crucial step in dendrochronology. Regional curve standardization (RCS) is a method where each tree-ring series is aligned according to cambial age (Briffa et al., 1992; Esper, et al., 2002; Esper et al., 2003). The RCS method preserves low frequency variability in long tree-ring data and still removes much of the variance associated with effects of tree age (Briffa et al., 1992; Esper et al., 2003; Bunn et al., 2004). The RCS method requires a large sample size for reliable results because the curve is fitted to the mean of all data rather than to individual series (Esper et al., 2002). Though the RCS method is influenced by multiple factors, RCS method is still robust to estimate biological growth trends i.e. preserving very long-term variability (Esper et al., 2003; Bunn et al., 2004).

To develop the RCS, all cores containing the piths were aligned by their cambial ages. For cores that did not include the pith, pith offsets (number of rings between the pith and the first ring in the core) were estimated using ring curvature and assuming a semi-circle (Eq. 1; Figure 2).

The formula for estimating the missing length from mid circle to the pith is given by;

$$r^2 = (c/2)^2 + (r - z)^2 \qquad \text{(Pythagorean Theorem)}$$

$$\therefore\ r = \frac{\left(\frac{c^2}{4}\right) + z^2}{2z} \qquad \text{Eq. (2),}$$

where, c is the length of chord in semi-circle ring, z is the length from chord to circle, and r is the radius of the circle.

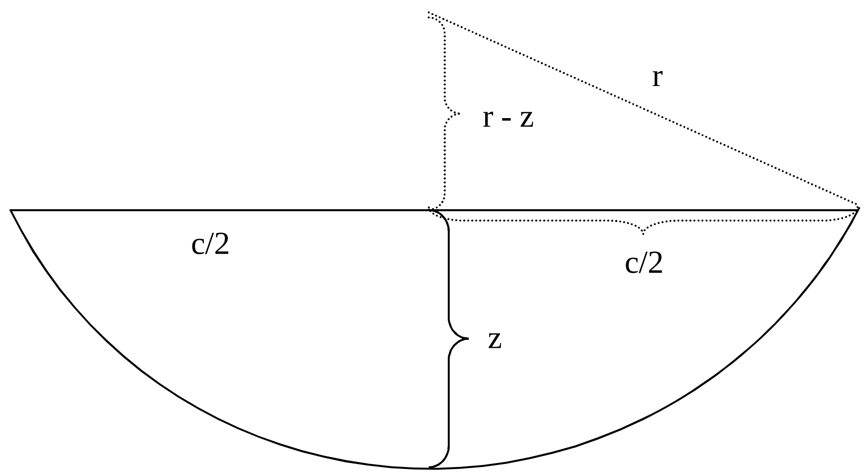

Figure 2: Definition sketch of semi-circle portion of a ring used in calculating pith offsets.

Parameter Estimation for RCS Curve Fitting and Detrending of Tree-ring Data

All tree-ring series aligned by their estimated cambial years were plotted against age to observe the pattern of biological growth. In general, tree radial growth decreases over time forming a negative exponential trend. The mean of all tree-ring series in the RCS was calculated and parameters of a single modified negative exponential model (Fritts, 1976) were estimated using maximum likelihood within PROC MODEL in SAS. The modified negative exponential regression equation is

$$y_{(t)} = a\, e^{-bt} + k \qquad \text{Eq. (3),}$$

where, a, b, and k are fitted parameters, e is the base of natural logarithm and y is the expected annual growth at year t.

After the RCS was fitted, each tree-ring series from different sites were then age-normalized using

$$I_t = O_{(t)} / y_{(t)} \qquad \text{Eq. (4),}$$

where, I_t is the age-normalized ring width and $O_{(t)}$ is the observed ring width at year t. The individual site chronologies for all sites were calculated as the mean of all age-normalized ring width series (I_t) from that site.

Climate Data

Climate data were acquired from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) database from 1935 to the start year of chronology for climate Division 8 of Louisiana. The climatic variables used in this analysis were monthly mean temperature, monthly precipitation, Palmer's Drought Severity Index (PDSI), and monthly Palmer's Hydrological Drought Index (PHDI). The National Weather Service calculates PDSI and PHDI to monitor drought and wetness conditions and they indicate moisture conditions during the growing season (Stahle et al., 1988). PDSI involves both dry and wet conditions and is based on precipitation, temperature and local available water content (AWC) of the soil (Palmer, 1965). PHDI is also a drought index and is used to evaluate long-term hydrological impacts (NCDC, 2010). The measurement units for temperature and precipitation were degree Celsius (^{o}C) and cm, respectively. The PDSI and PHDI are unitless.

River Stage Data

Long-term river stage data for this analysis were not available for many sites except in the Atchafalaya Basin. However, the Atchafalaya Basin does not represent other sites in terms of river stage characteristics. Therefore, instead of attempting to use site-specific data, only general data on river stage and coastal water level records were used. Monthly stage data of the Mississippi River at Baton Rouge, Louisiana (station ID 01160) were acquired from US Army Corps of Engineers (USACE) because it has the longest record for south Louisiana and represents approximate hydrologic conditions across wide range of the study areas. The record at this station began in 1935. The river stage variables were indicated by an abbreviation, H.

The river stage data at Baton Rouge were correlated to those of Lower Atchafalaya River at Morgan City (station ID 03780), Lake Verret at Attakapas Landing (station ID 052720) and coastal water level data at Grand Isle (Figure 3).

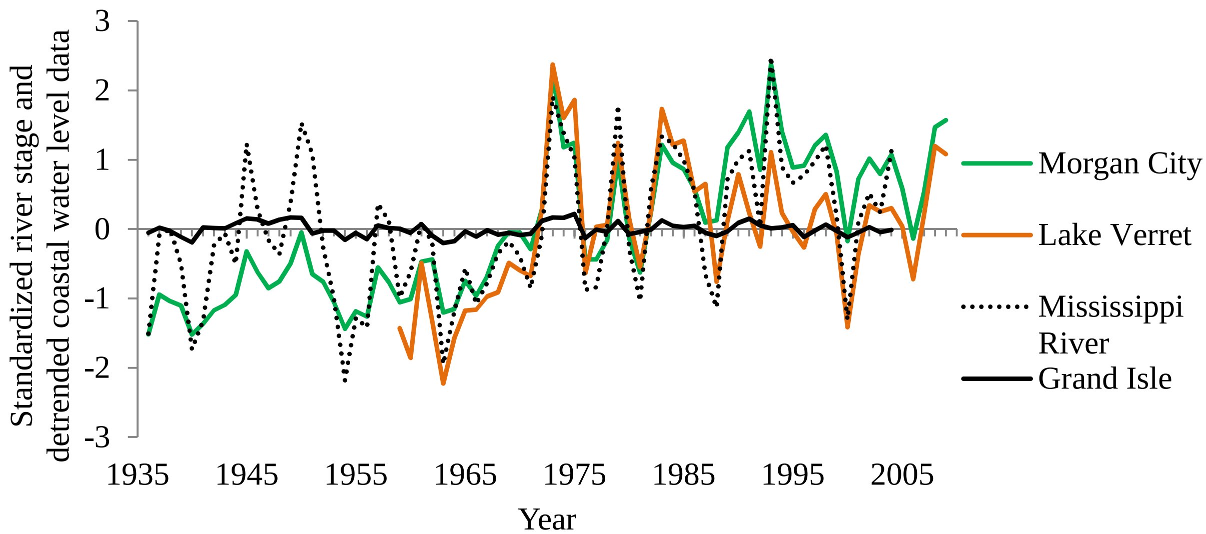

Figure 3: River stage data from Mississippi River at Baton Rouge, Morgan City and Lake Verret stations and the coastal water level in southeastern Louisiana.

Coastal Water Level Data

Coastal water level data on mean sea level (MSL) for Grand Isle (station ID 8761724), Louisiana were acquired from the National Oceanic and Atmospheric Administration (NOAA) (http://tidesandcurrents.noaa.gov). Because some monthly records from the 1974 year in Galveston Pier 21 (Ti_Galveston) station were missing, another station, Rockport (ID 8774770), Texas, was used to reconstruct that missing period (Tables 2-3). Also, because the record from the Grand Isle extended only from 1978 to present, another station, Galveston Pier 21 (ID 8771450), Texas, was used to reconstruct the Grand Isle records from 1935-1977 using multiple linear regressions (Tables 4-5, Figure 4). Finally, the modeled values for months of 1974 of the Galveston Pier 21 (ID 8771450) using Rockport as predictor variable were used to fill up the missing monthly records of the year 1974 of the Galveston Pier 21 station. The variables year and the month were also considered in the model because they had statistically significant effect in correlations. The coastal water level variables were indicated by an abbreviation, Ti .

Table 2: Type 3 tests of fixed effects of full model significance on reconstruction of coastal water level of Galveston Pier 21, Texas using those from Rockport, Texas (Ti_RockTX).

Effect	F-value	Pr > F
Ti_RockTX	148.8	<.0001
Year	3.87	0.05
Month	11.61	<.0001

Table 3: Parameter estimates of model on reconstruction of coastal water level of Galveston Pier 21, Texas using those from Rockport, Texas.

Effect	Estimate	Standard Error	DF	t	Pr > |t|
Intercept	-1.951	0.985	393	-2	0.048
Ti_RockTX	0.583	0.048	393	12.2	<.0001
Year	0.001	0.001	393	1.97	0.05
Month 1	0.011	0.017	393	0.61	0.543
Month 2	0.027	0.017	393	1.59	0.114
Month 3	0.053	0.017	393	3.06	0.002
Month 4	0.06	0.018	393	3.4	<0.001
Month 5	0.042	0.018	393	2.26	0.024
Month 6	0.017	0.018	393	0.97	0.332
Month 7	0.051	0.017	393	2.95	0.003

Continued Table 3

Effect	Estimate	Standard Error	DF	t	Pr > |t|
Month 8	0.118	0.017	393	6.82	<.0001
Month 9	0.124	0.019	393	6.34	<.0001
Month 10	0.023	0.02	393	1.18	0.241
Month 11	-0.009	0.018	393	-0.52	0.603
Month 12	0	.	.	.	.

All these procedures were performed using PROC MIXED in SAS. The R^2, which is a percentage of variance explained by the predictor variables on the response variable, for the model in reconstructing missing period of monthly records of 1974 in Galveston Pier 21 station using Rockport station was 0.64. The R^2 for the model in reconstructing missing records of Grand Isle station using Rockport station was 0.94.

Table 4: Type 3 tests of fixed effects of full model significance on reconstruction of missing records of coastal water level of Grand Isle, Louisiana (ID 8761724) using Galveston Pier 21, Texas (Ti_Galveston).

Effect	F-value	Pr > F
Ti_Galveston	1115.4	<.0001
Year	255	<.0001
Month	25.24	<.0001

Table 5: Parameter estimates of model on reconstruction of missing records of coastal water level of Grand Isle, Louisiana (ID 8761724) using Galveston Pier 21, Texas.

Effect	Estimate	Standard Error	DF	t	Pr > |t|
Intercept	-1.951	0.985	393	-2	0.048
Ti_RockTX	0.583	0.048	393	12	<.0001
Year	0.001	0.001	393	2	0.05
Month 1	0.011	0.017	393	0.6	0.543
Month 2	0.027	0.017	393	1.6	0.114
Month 3	0.053	0.017	393	3.1	0.002
Month 4	0.06	0.018	393	3.4	<0.001
Month 5	0.042	0.018	393	2.26	0.024
Month 6	0.017	0.018	393	0.97	0.332

Continued Table 5

Effect	Estimate	Standard Error	DF	t	Pr > |t|
Month 7	0.051	0.017	393	2.95	0.003
Month 8	0.118	0.017	393	6.82	<.0001
Month 9	0.124	0.02	393	6.34	<.0001
Month 10	0.023	0.02	393	1.18	0.241
Month 11	-0.009	0.018	393	-0.5	0.603
Month 12	0	.	.	.	.

The coastal water level data were detrended because there was a time related trend in these data (Figure 4). First, each monthly coastal water level data ranging from 1936-2004 were separately fitted with a simple linear regression with year as a predictor variable. The coastal water level data were then detrended as the observed value less the value modeled from the fitted regression.

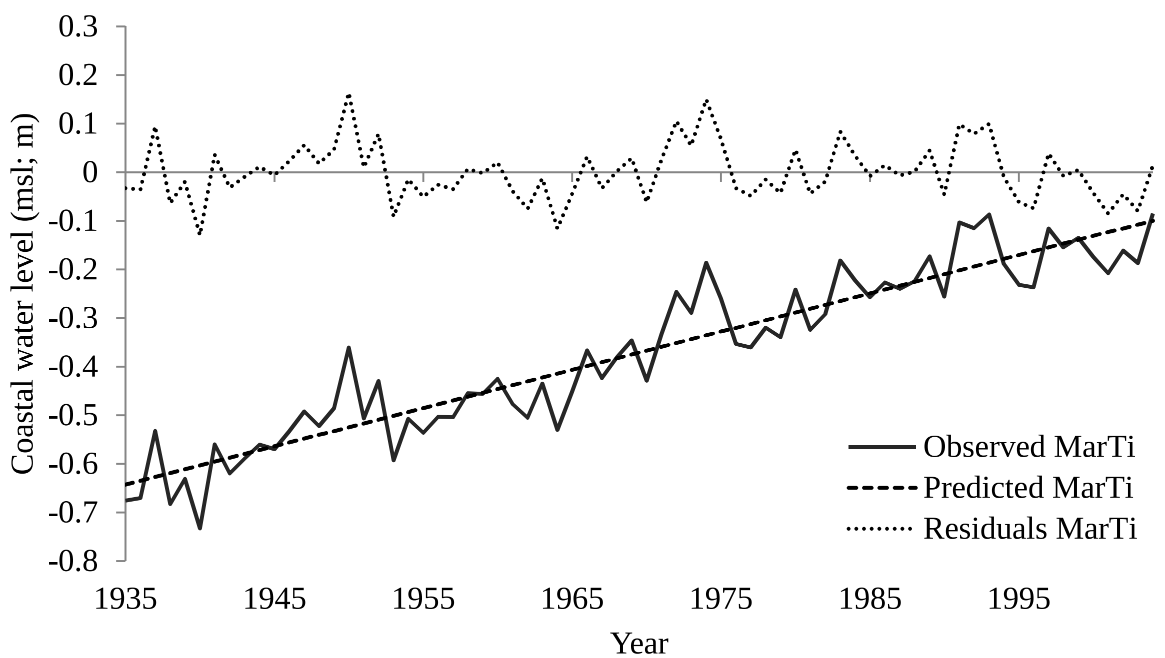

Figure 4: Example of observed, predicted and residual values current year's March coastal water levels at Grand Isle as reconstructed from Galveston station. Residuals (MarTi) are a residual coastal water level chronology obtained after detrending using predicted values.

Grouping Climatic and Hydrologic Variables

The oldest river stage data for the station at Baton Rouge were from 1935. The analysis was confined between 1936 and 2004 because the previous year's data of river stage for 1934 were not available. Similarly, the most recent date for tree-ring data of all sites was 2004.

Tree growth response has often been found to correspond to various combinations of monthly climatic and hydrologic variables of previous and current years. Generally, the term used in dendrochronology to indicate the length of period that the trees respond to these variables is called the dendroclimatic period (Fritts, 1976). Experience and exploratory analysis revealed few significant correlations between growth and variables more than one year removed from the year of ring formation, so 19 monthly variables were formed starting from March of the previous year to September of the year in which the ring was formed based on the growing season in south Louisiana (Eggler, 1955). These variables were constructed for every climatic and hydrologic monthly variable, resulting in 114 monthly variables. Based on ranges of similar correlations of the variables with tree radial growth, the climatic and hydrologic variables were subjectively grouped across multiple months and the new composite variable was defined as the mean for the entire period. Altogether, 44 variables were formed as a result of the grouping process. In the process of grouping, either ungrouped monthly or grouped variables were formed based on similar correlations. There is always a difficulty of correct interpretation about the positive or negative relationship between tree radial growth and an individual variable because trees mostly respond to certain periods of climate and hydrology. Therefore, interpretations about the relationship between tree radial growth and hydrologic and climatic variables were made only for the selected ungrouped or grouped variables.

Correlation Analysis and Spatial Assessment of Pattern of Linear Relationships

Correlation measures between 22 tree-ring chronologies and ungrouped and grouped monthly climatic and hydrologic variables were calculated to measure the strength of linear relationships between tree radial growth and these environmental variables.

To assess the spatial variability of response to the hydrologic and climatic variables, the sites were categorized into three groups, depending upon their locations in deltaic inter-distributary basins (Coleman and Roberts, 1988), namely Atchafalaya, Lake Pontchartrain, and Lake Verret basins (Figure 1; Table 6). Rather than interpreting site-specific differences, the focus was on the basin-level difference in response of tree radial growth to hydrologic and climatic variables. In the course of finding the hydrologic and climatic variables that had a distinct pattern of variability in terms of correlation values of these variables with tree radial growth across basins, 114 and 44 analyses of variance (ANOVAs) were performed for each ungrouped hydrologic and climatic variable and for all grouped variables, respectively, to test for the basin-level differences in correlation measures between environmental variables and tree radial growth at these basins.

Table 6: Grouping of different sites into three basin group based on the their locations.

SN	Group	Sites included[1]
1.	Atchafalaya Basin (A)	BBL, BCL, BLBLC, BP, LL, PLS, SM, VS, VU
2.	Lake Pontchartrain Basin (LP)	EL, JBB, LB, SX, TL, WC, WL
3.	Lake Verret Basin (LV)	AT, EH, GC, TC, TO, TT

[1]**AT**=Attakapas; **BCL**=Bayou Cowan Low-flow; **BP**=Bayou Pigeon; **BBL**=Bee Bayou Low-flow; **BLBLC**=Berry Lake; **EH**=Elm Hall; **EL**= Bonnet Carré East Levee; **GC**=Godchaux Canal; **JBB**=Joyce WMA Black Bayou; **LB**=LaBranche; **LL**=Long Lake; **PLS**=Pierce Lake South; **SM**= Six Mile North; **SX**= Bonnet Carré Suxion Canal; **TC**= Thibodaux Control; **TL**= Bayou Traverse and LaBranche; **TO**= Thibodaux Outflow ; **TT**=Thibodaux Treatment; **VU**= Verdunville; **VS**= Verdunville South / Grayhorse; **WC**= LaBranche Walker Canal; **WL**= LaBranche West Levee

The possible variables, either individual monthly or grouped variables, were plotted within a GIS to provide spatial assessment of strength of correlation across basins based on cutoff point for statistical significant correlation value and significant p-values from the ANOVA tests for both ungrouped and grouped variables. The significant cutoff point of correlation value (0.236) was obtained based on relation between sample size and student's t-distribution value at alpha 0.05.

Redundancy Discriminant Analysis (RDA)

To analyze the relationship between multivariate responses (multiple site tree-ring chronologies) and multivariate explanatory variables of climate and hydrology in space, redundancy discriminant analysis (RDA) (Rao, 1964; Wollenberg, 1977) was used. Redundancy discriminant analysis models multivariate response to a set of multivariate explanatory variables (Rao, 1964; Jongman, 1987; Legendre and Legendre, 1998). The RDA may also be understood as multivariate multiple linear regressions (Legendre and Legendre, 1998). In RDA, first multivariate regression is performed between multivariate response variables and multivariate explanatory variables to find the fitted values for response variables and then principal component analysis is performed on fitted values of response variables. Once principal components are obtained from PCA on fitted response data, these principal components are again modeled with multivariate explanatory variables to obtain canonical ordination vectors that are linear combinations of the original explanatory variables (Jongman, 1987; Legendre and Legendre, 1998). There are few studies using redundancy discriminant analysis to explore climate-tree-growth relationships. Examples of such use include Friedrichs et al., (2008), and Scharmweber et al., (2011).

In my case, the multivariate response variables were tree-ring chronologies from 22 sites and explanatory variables were the multivariate data set containing climatic and hydrologic variables. Since there were too many variables to include in a single RDA, correlation analysis between regional average tree radial growth and all 65 variables was performed and variables having correlation greater than 0.15 were included in RDA. To avoid multicollinearity, a high correlation among predictor variables, variables having inflation factor greater than 10 were removed based on their corresponding correlation with regional average tree-ring index (Stevens, 2002). Inflation factor is a measure of multicollinearity among independent variables. The variables with lowest correlation among those having inflation factor greater than 10 were removed until all inflation factors were reduced to less than 10.

Redundancy discriminant analysis was performed using CANOCO 4.5 (Ter Braak and Smilauer 2002). The set of site data was standardized within CANOCO 4.5. Redundancy discriminant analysis was also performed on climatic and hydrologic variables selected based on the result from ANOVAs and threshold for significant correlation value mentioned earlier and 22 tree-ring site chronologies. The RDA was also performed on those climatic and hydrologic variables and three basins-averaged tree-ring chronologies. The relationships between tree radial growth and environmental variables were summarized using bi-plots by overlaying environmental variables on ordination vectors obtained from RDA.

RESULTS AND DISCUSSION

Modeling Age Related Growth Trend

Overall, the individual baldcypress trees from the research sites yielded a negative exponential curve in radial growth over age, which is common (Speer, 2010). To adjust for the age-related growth trend in a tree-ring series, a negative exponential curve was fitted on the RCS averaged chronology (Figure 5). Sensitivity of parameters was checked by fitting two cutoffs to see the effect of old trees in the parameter estimates. The cutoff of ≤ 180 years was used to fit the curve and to find the parameter estimates of the negative exponential fitted line (Table 7). The fitted line estimated using cutoff of ≤ 180 years was used to standardize individual tree-ring series (Figure 6). Throughout this document, tree radial growth means age-normalized tree radial growth obtained after detrending.

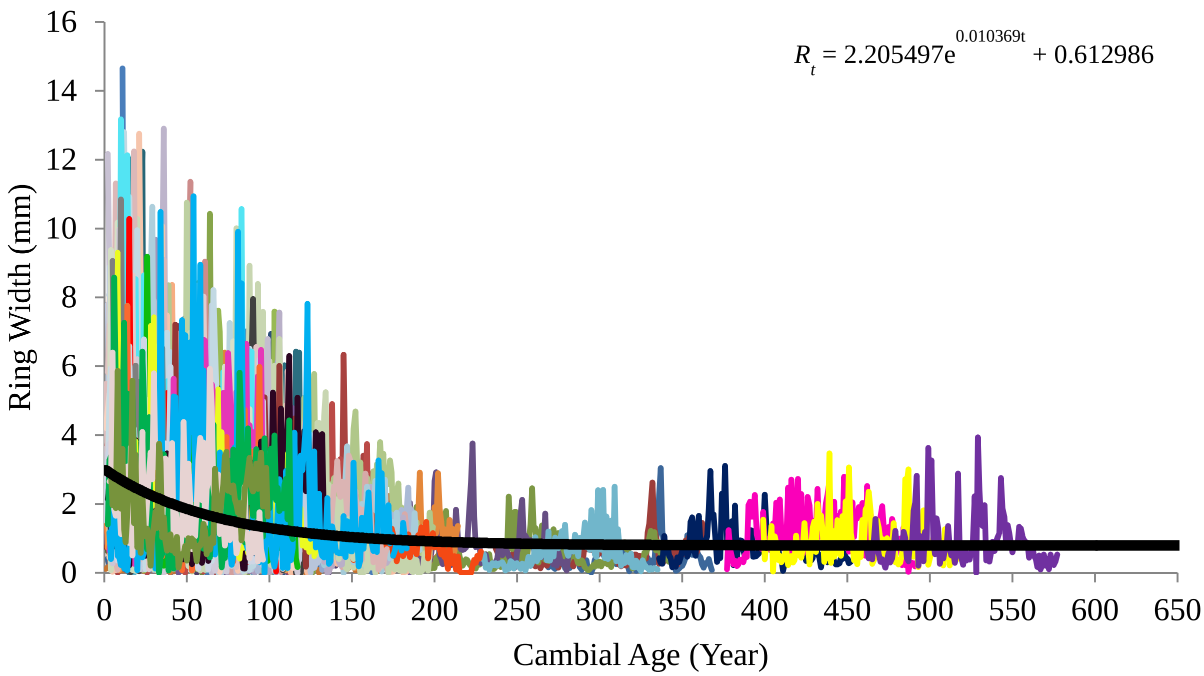

Figure 5: Negative exponential fitted curve of Regional Curve Standardization (RCS) data to model age-related growth trend in tree-ring widths. Trees from all sites are plotted and indicated with different colors (n=255). R_A is a raw ring width.

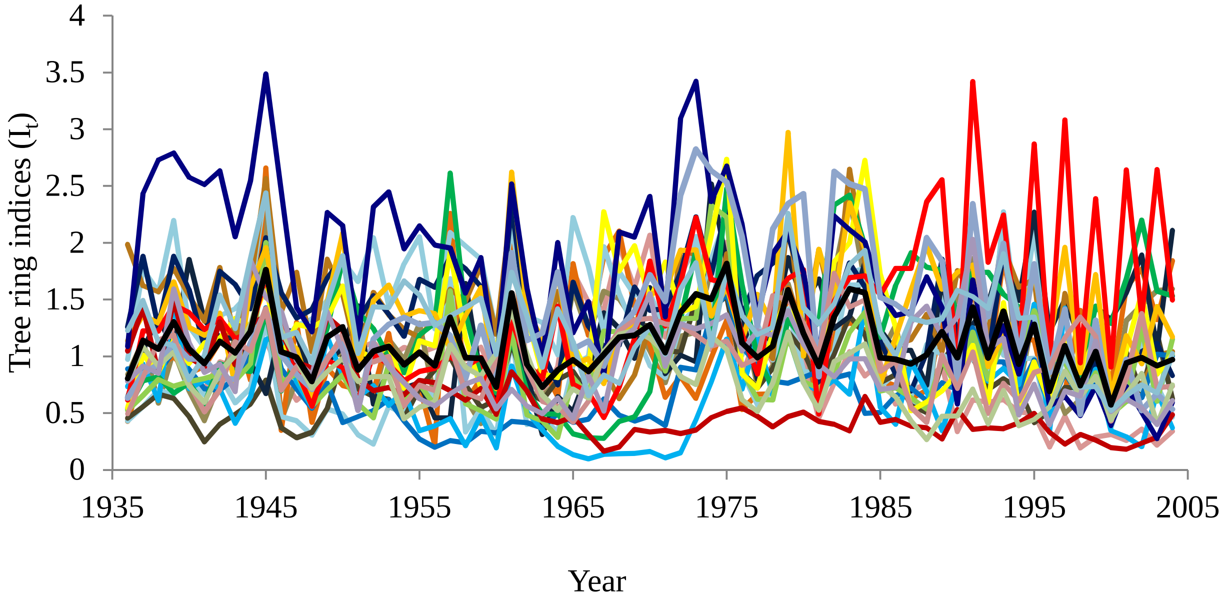

Figure 6: Age-adjusted tree radial growth, I_t, for all 22 sites and their average. Each color represents an individual site and black represents the mean. These are radial growth obtained after adjusting for age-related growth trend.

Table 7: Parameter estimates of negative exponential fit for two cutoff cambial ages.

Cutoffs of cambial age of trees	Parameters		
(Years)	a	b	k
≤ 180	2.205497	0.010369	0.612986
≤ 577	2.221557	0.014675	0.78687

Temporal Variation in Tree-ring Growth

Significant positive correlations among chronologies indicate the common year to year variation in growth among the sites (Table 8). There was a high significant positive correlation among chronologies for most sites. Some sites had negative significant correlation with other sites. Sites without significant correlations indicated the different year to year variation in radial growth.

Table 8: Correlation coefficients among raw (R_t) tree-ring chronologies. Both column and row headings are abbreviated site names.

Site[1]	AT	BBL	BCL	BLBLC	BP	EH	EL	GC	JBB
BBL	0.4831	1							
BCL	0.3132	0.6661	1						
BLBLC	0.4319	0.6372	0.5196	1					
BP	0.4608	0.3319	0.1756*	0.6563	1				
EH	0.8326	0.5259	0.3558	0.4552	0.5340	1			
EL	0.3167	0.1781*	0.0960*	0.1001*	-0.0173*	0.4146	1		
GC	0.6789	0.4782	0.2739	0.4662	0.3399	0.7271	0.5239	1	
JBB	-0.2118	0.2295	0.0436*	0.2961	0.0560*	-0.2045*	-0.0058*	-0.0669*	1
LB	0.1456*	0.0735*	0.0347*	0.3610	0.3317	0.3481	0.5033	0.4284	0.1524*
LL	0.0914*	0.3796	0.1932*	0.2869	0.1867*	0.2202	0.1813*	0.3526	0.1553*
PLS	0.5613	0.6281	0.5177	0.8646	0.7093	0.6085	0.1976*	0.5463	0.2129
SM	0.6390	0.6329	0.4659	0.4618	0.2670	0.6047	0.2612	0.5154	-0.0051*
SX	0.3539	0.2080*	0.0729*	0.1225*	0.0590*	0.2731	0.6047	0.4059	0.0130*
TC	0.2075*	0.1602*	0.1541*	0.5452	0.6423	0.3183	0.0551*	0.2865	0.2362
TL	0.3712	0.0398*	0.0181*	0.2452	0.4807	0.5417	0.5081	0.5534	-0.2686
TO	0.6569	0.2811	0.1550*	0.4349	0.4677	0.6191	0.4954	0.7048	-0.1630*
TT	0.4978	0.4195	0.0792*	0.5894	0.6251	0.4140	0.1267*	0.4220	0.2374
VS	0.5226	0.4128	0.3484	0.5517	0.6857	0.6490	0.2128	0.4340	0.0487*
VU	0.5942	0.2969	0.3041	0.3833	0.4886	0.7244	0.4735	0.5189	-0.2077*
WC	0.3530	0.2023*	0.0269*	0.3256	0.3393	0.3255	0.3662	0.3723	0.2721
WL	0.4032	0.2552	0.0624*	0.4099	0.6552	0.4820	0.4381	0.5036	-0.05177*

*coefficients not significant at α=0.05

[1]**AT**=Attakapas; **BCL**=Bayou Cowan Low-flow; **BP**=Bayou Pigeon; **BBL**=Bee Bayou Low-flow; **BLBLC**=Berry Lake; **EH**=Elm Hall; **EL**= Bonnet Carré East Levee; **GC**=Godchaux Canal; **JBB**=Joyce WMA Black Bayou; **LB**=LaBranche; **LL**=Long Lake; **PLS**=Pierce Lake South; **SM**= Six Mile North; **SX**= Bonnet Carré Suxion Canal; **TC**= Thibodaux Control; **TL**= Bayou Traverse and LaBranche; **TO**= Thibodaux Outflow ; **TT**=Thibodaux Treatment; **VU**= Verdunville; **VS**= Verdunville South / Grayhorse; **WC**= LaBranche Walker Canal; **WL**= LaBranche West Levee

Continued Table 8

Site[1]	LB	PLS	SM	SX	TC	TL	TO	TT	VS	VU	WC
LL	0.2108										
PLS	0.4355	1									
SM	0.0932*	0.5652	1								
SX	0.3862	0.2133	0.2332	1							
TC	0.5099	0.5465	0.0528*	0.1527*	1						
TL	0.6826	0.4417	0.1426*	0.2058*	0.4104	1					
TO	0.5070	0.5982	0.3508	0.4257	0.4921	0.7290	1				
TT	0.3234	0.6033	0.3544	0.3879	0.6359	0.2013*	0.5874	1			
VS	0.3925	0.6471	0.5585	0.1722*	0.4656	0.4321	0.4530	0.4559	1		
VU	0.3988	0.5357	0.4979	0.1181*	0.3382	0.6844	0.6033	0.2031*	0.7443	1	
WC	0.5197	0.4412	0.1904*	0.4191	0.4539	0.4637	0.5962	0.4779	0.4034	0.4016	1
WL	0.5819	0.5573	0.1975*	0.4786	0.4947	0.6879	0.6573	0.5759	0.4479	0.3910	0.4721

*coefficients not significant at α=0.05

[1]**AT**=Attakapas; **BCL**=Bayou Cowan Low-flow; **BP**=Bayou Pigeon; **BBL**=Bee Bayou Low-flow; **BLBLC**=Berry Lake; **EH**=Elm Hall; **EL**= Bonnet Carré East Levee; **GC**=Godchaux Canal; **JBB**=Joyce WMA Black Bayou; **LB**=LaBranche; **LL**=Long Lake; **PLS**=Pierce Lake South; **SM**= Six Mile North; **SX**= Bonnet Carré Suxion Canal; **TC**= Thibodaux Control; **TL**= Bayou Traverse and LaBranche; **TO**= Thibodaux Outflow ; **TT**=Thibodaux Treatment; **VU**= Verdunville; **VS**= Verdunville South / Grayhorse; **WC**= LaBranche Walker Canal; **WL**= LaBranche West Levee

Redundancy Discriminant Analysis Result

The total variation in tree-ring data explained by the combination of environmental variables was 63.6% (Table 9). The first RDA axis explained 28 % of the total variability in the tree-ring data which was higher than the remaining axes. Moreover, all four axes were correlated with the tree-ring data. However, the first and second axes had higher correlations with the tree-ring data (r=0.887 and r=0.834, respectively, Table 9) than other axes.

Table 9: Results of redundancy discriminant analysis performed between a set of 22 site indices and another set of 31 climatic and hydrologic variables. All four eigenvalues are canonical and correspond to axes that are constrained by the environmental variables

Axes	**1**	**2**	**3**	**4**	**Total variance**
Eigenvalues:	0.28	0.108	0.076	0.035	1
Tree-ring-environment correlations:	0.887	0.834	0.795	0.793	
Cumulative percentage variance					
of tree-ring data:	28	38.7	46.4	49.9	
of tree-ring-environment relation:	44	60.9	72.9	78.4	
Sum of all eigenvalues					1
Sum of all canonical eigenvalues					0.636

To avoid the problem of multicollinearity in RDA, 31 variables were selected for the RDA model based on the correlation of those variables with detrended tree radial growth and the inflation factor and the correlation of those variables with tree radial growth (Table 10).

An ordination diagram is a major approach to describe the results of RDA produced from CANOCO 4.5 (Lepš and Šmilauer, 2003). Here, the Figure 9 is referred to explain how to interpret the ordination diagram in the context of this study. It is a multivariate ordination diagram of RDA of standardized tree radial growth at sample sites, which are represented by red abbreviated form and climatic and hydrologic variables from Table 10, which are represented by arrows. The XY co-ordinates are first and second RDA ordination axes. The symbols α_1 and α_2 represent the angles between tree radial growth at Atchafalaya site and Jul_SepH variable and tree radial growth at the Atchafalaya site and PreJunP variable, respectively. The triangle at the centroid represents the orthogonal relation between tree radial growth at the Atchafalaya site and PreJunP variable. The length of an arrow toward site names represents the strength of linear relationship between the variable and tree radial growth at sites. When an arrow is opposite to a site, it represents a negative correlation between environmental variable and tree radial growth at that site. When the vector is orthogonal to a site, it represents no correlation of that vector with tree radial growth at that site. Therefore, this means the longer the vector towards the sites, the more important the climatic and hydrological parameter. The strength of relationship also depends upon the angle that is made between the site and climatic and hydrologic variables. For example, in Figure 9, tree radial growth at the Atchafalaya site has a relatively larger positive correlation with JunH than with Jul_SepH because the Atchafalaya site and JunH point closely to the same direction and Jul_SepH is little further away from Atchafalaya site. The tree radial growth at Atchafalaya and PreJunP are almost non-correlated because these are almost orthogonal to each other. Therefore, as sites and climatic and hydrologic variables are away from each other, correlation between these variables decrease and the correlation starts to become negative when these two variables are opposite to each other. For example, in Figure 9, tree radial growth at the Atchafalaya has negative correlation with PreAugT because these two are opposite to each other. The bi-plot projection of the site head tips onto the arrow of the climatic and hydrologic variables provides a more precise approximation (Lepš and Šmilauer, 2003).

Table 10: Selected climatic and hydrologic variables included in RDA, their weighted mean, standard deviation and inflation factor.

Variable	Units[1]	Weighted mean	Inflation Factor	Variable full name[2]
PreMarT	°C	16.062	1.704	Previous year's March temperature
PreAprMayT	°C	21.932	1.717	Previous year's April through May temperature
PreJunJulT	°C	27.236	2.012	Previous year's June through July temperature
PreAugT	°C	27.581	2.189	Previous year's August temperature
PreSepOctT	°C	23.035	2.089	Previous year's September through October temperature
PreNov_MarT	°C	13.554	3.198	Previous year's November through March temperature
Apr_SepT	°C	25.226	2.450	Current year's April through September temperature
PreMar_MayP	cm	11.770	2.388	Previous year's March through May precipitation
PreJunP	cm	15.561	1.911	Previous year's June precipitation
PreJulP	cm	18.310	2.229	Previous year's July precipitation
PreAugSepP	cm	15.163	2.336	Previous year's August through September precipitation
PreOctP	cm	9.532	1.964	Previous year's October precipitation
AprMayP	cm	11.944	5.602	Current year's April through May precipitation
JunP	cm	15.777	3.253	Current year's precipitation
Jul_SepP	cm	16.086	2.618	Current year's July through September precipitation
May_SepPH	-	0.101	8.639	Current year's May through September Palmer's Hydrological Drought Index
PreMar_NovH	m	5.132	3.655	Previous year's March through November river stage
PreDecH	m	4.407	3.609	Previous year's December river stage
Jan_MarH	m	6.567	5.107	Current year's January through March river stage
Apr_MayH	m	8.165	2.779	Current year's April through May river stage
JunH	m	6.524	3.242	Current year's June river stage
Jul_SepH	m	3.312	2.641	Current year's July through September river stage
Premar_MayTi	m	0.000	3.385	Previous year's March through May coastal water level
PreJunTi	m	0.000	2.266	Previous year's June coastal water level
PreJulTi	m	0.000	2.498	Previous year's July coastal water level

[1] °C= Degree Celsius; [2]The short-formed variable is the mean of all months from first through last months stated.

Continued Table 10

Variable	Units[1]	Weighted mean	Inflation Factor	Variable full name[2]
PreAug_OctTi	m	0.000	4.119	Previous year's August through October coastal water level
PreNovDecTi	m	0.000	2.834	Previous year's November through December coastal water level
Jan_MarTi	m	0.000	4.348	Current year's January through March coastal water level
AprMayTi	m	0.000	3.847	Current year's April through May coastal water level
JunJulTi	m	0.000	2.367	Current year's June through July coastal water level
AugSepTi	m	0.000	2.029	Current year's August through September coastal water level

[1] °C= Degree Celsius; [2]The short-formed variable is the mean of all months from first through last months stated.

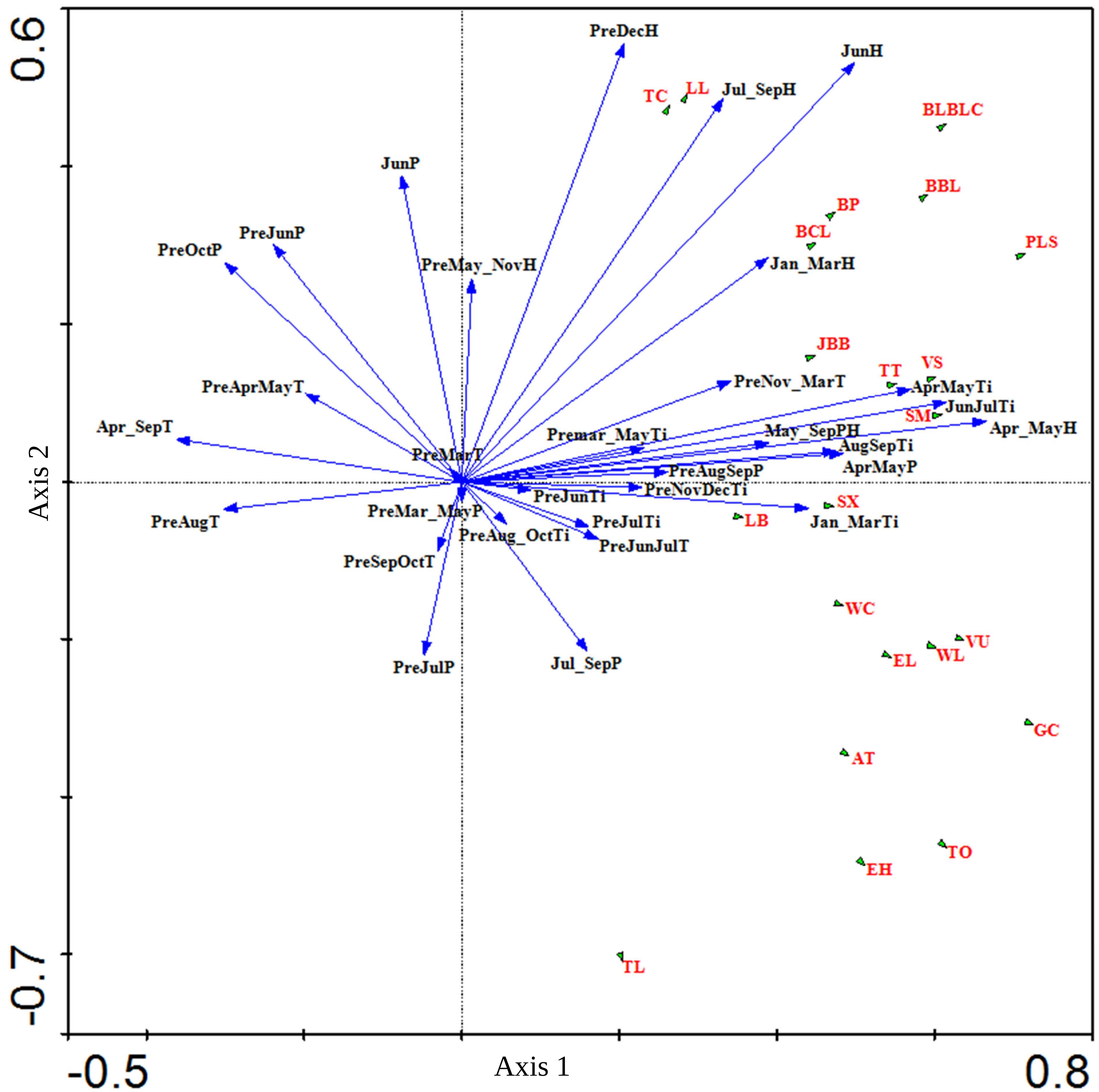

Figure 7: Multivariate ordination diagram of RDA of standardized tree radial growth at sample sites (represented by red abbreviated form), and climatic and hydrologic variables from Table 10 (represented by arrows). The XY co-ordinates are first and second axes. The length of the arrow toward site names represents the strength of linear relationship between the variable and tree radial growth at sites; the longer the vector towards the sites, the more important the climatic and hydrological parameter. When an arrow is opposite to a site, it represents a negative correlation between environmental variable and tree radial growth at that site. When the vector is orthogonal to a site, it represents no correlation of that vector with tree radial growth at that site.

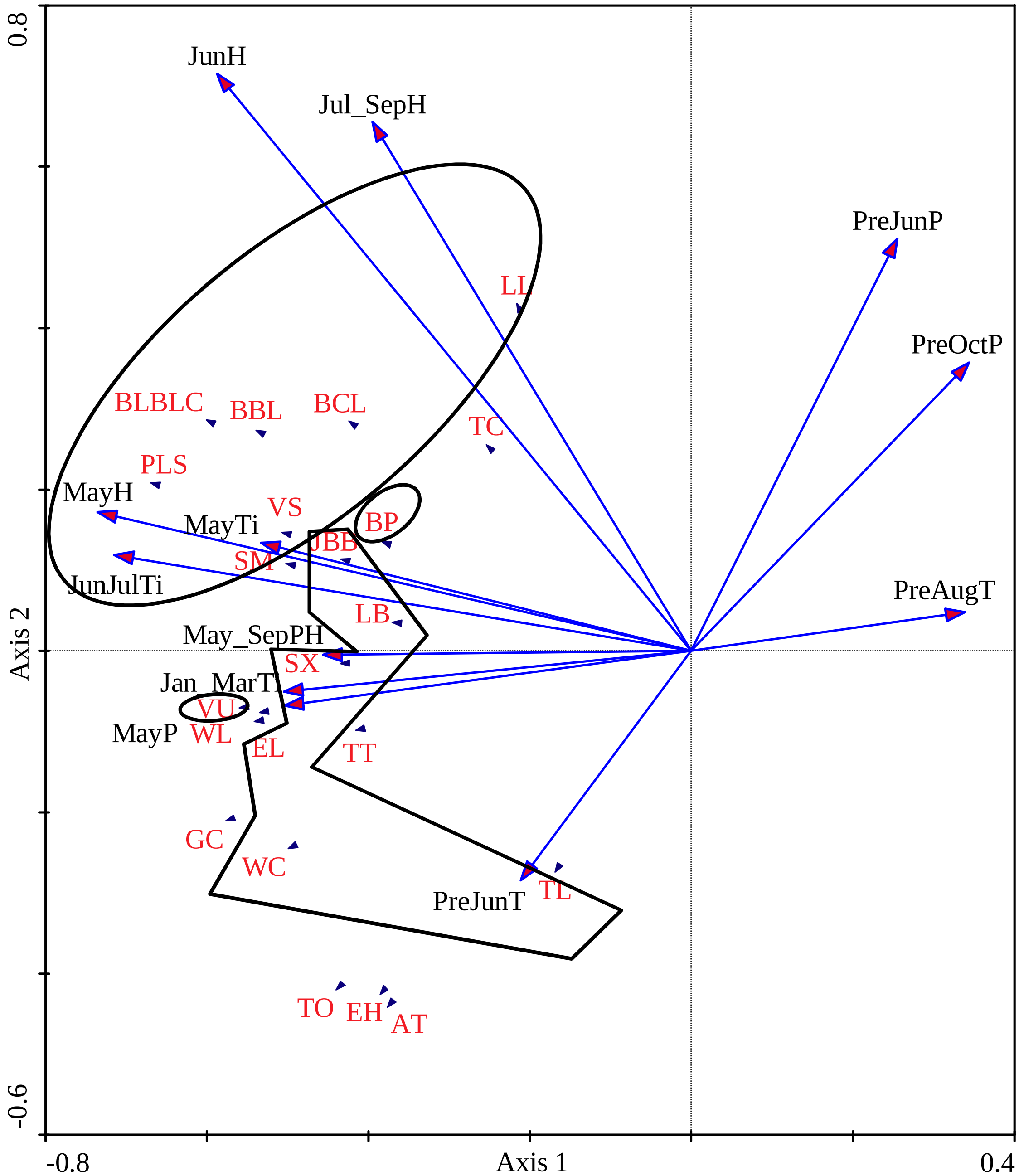

Figure 8: Multivariate ordination diagram of RDA of standardized tree radial growth at individual sites (represented by red abbreviated form) and selected climatic and hydrologic variables of spatial importance (represented by arrows). The XY co-ordinates are first and second axes. The length of the arrow toward site names represents the strength of linear relationship between the variable and tree radial growth at sites; the longer the vector towards the sites, the more important the climatic and hydrological parameter. When an arrow is opposite to the sites, it represents negative correlation between environmental variables and tree radial growth at those sites. When the vector is orthogonal to a site, it represents no correlation of that vector with tree radial growth at that site. The ellipses (including all larger and smaller ones) represent the Atchafalaya basin sites and the polygon represents Lake Pontchartrain basin sites. The remainder represents the Lake Verret basin.

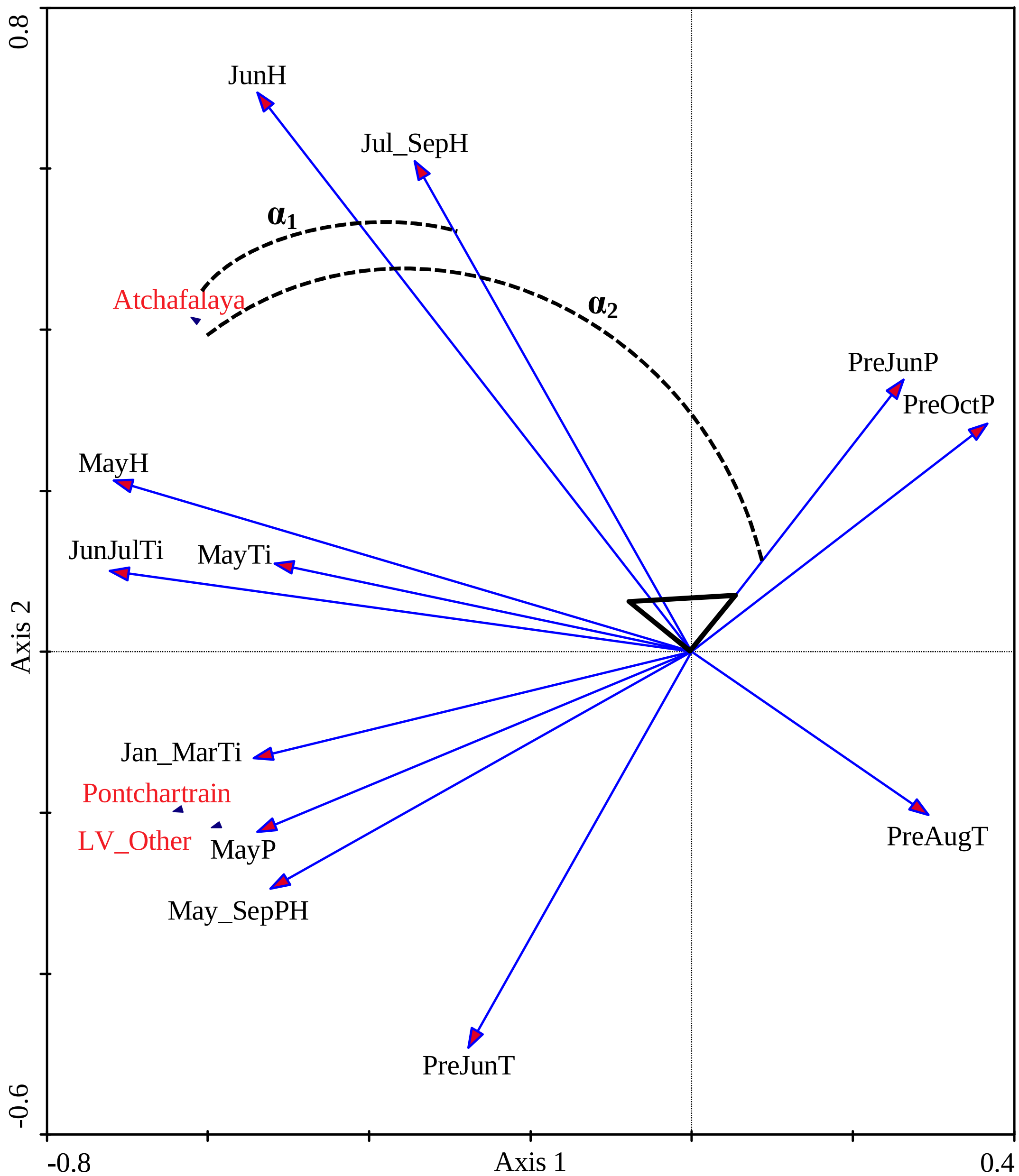

Figure 9: Multivariate ordination diagram of RDA of standardized tree radial growth in each of the three selected basins (represented by red font) and selected climatic and hydrologic variables of spatial importance (represented by arrows). The XY co-ordinates are first and second axes. The length of the arrow toward site names represents the strength of linear relationship between the variable and tree radial growth at sites; the longer the vector towards the sites, the more important the climatic and hydrological parameter. When an arrow is opposite to the sites, it represents negative correlation between environmental variables and tree radial growth at those sites. When the vector is orthogonal to a site, it represents no correlation of that vector with tree radial growth at that site. The symbols, α_1 and α_2, represent the angles between tree radial growth at Atchafalaya site and Jul_SepH variable and tree radial growth at Atchafalaya site and PreJunP variable, respectively.

River Stage and Tree Radial Growth Relationship

The box and whisker plot of correlations between the Mississippi River (stage) and tree radial growth (Figure 10) showed that a few current-year individual monthly river stage variables were significantly positively correlated with tree radial growth. The current-year variables, AprH, MayH, JunH, and maybe SepH, had significant positive correlation with tree radial growth than other river stage variables overall.

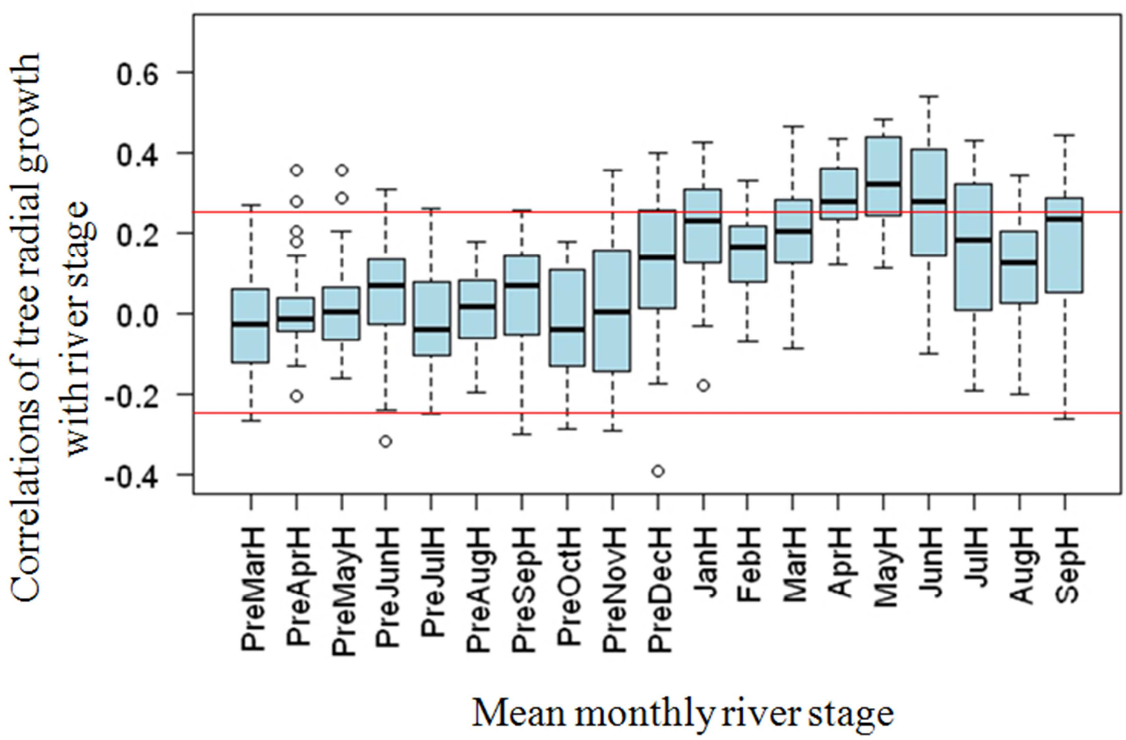

Figure 10: Box and whisker plot of correlations between detrended tree radial growth and mean monthly river stage variables. The absolute value of correlation below the lower red line or above the upper red line represent the level of statistical significance at α = 0.05.

Multivariate ordination results (Figure 7) illustrate the relative strength of the correlations among environmental variables measured and the radial growth trends at the selected sites. PreDecH and JulSepH were strongly positively correlated with cypress radial growth at theTC and LL sites (Figure 7). JunH was the strongest positively correlated river stage variable with cypress radial growth at the TC, LL, BCL, BP, BBL, and BLBLC sites (Figure 7). Jan_MarH was also strongly positively correlated with cypress radial growth at the BBL, BCL, BLBLC and BP sites. While Apr_MayH was another strong river stage variable positively correlated with cypress radial growth at the SM, TT, and VS sites (Figures 7 and 10).

River stage was positively correlated with tree radial growth at almost every site except VU in the Atchafalaya Basin (Figures 8 and 9) whereas there was less consistent response of Lake Pontchartrain and Lake Verret Basin sites to river stage (Figures 8, 11, 12, and 13).

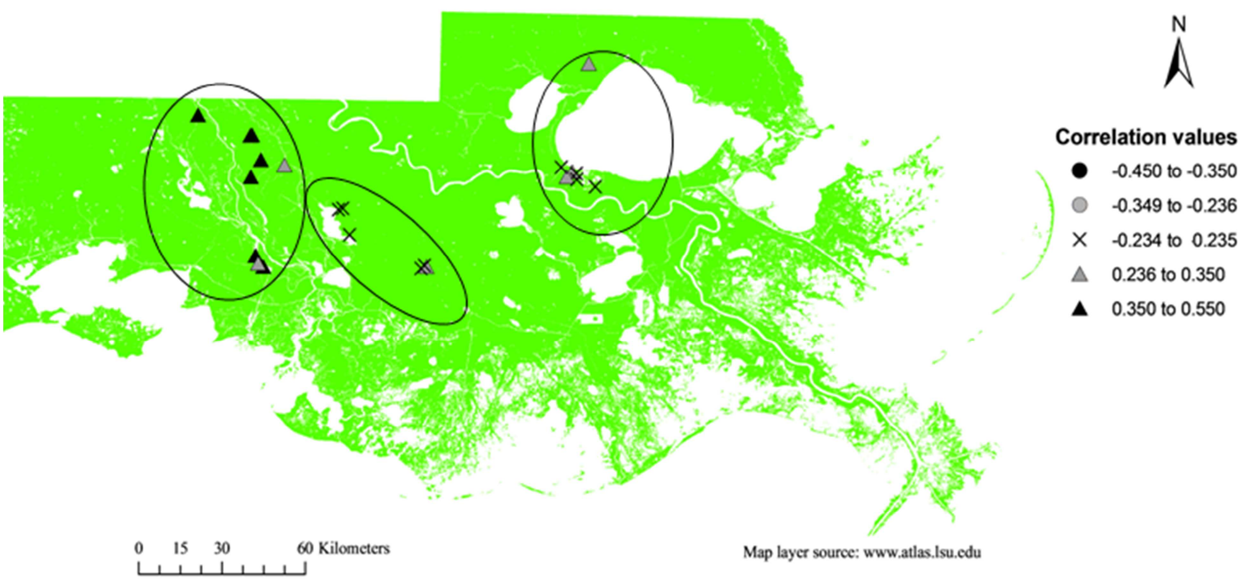

Figure 11: Spatial pattern of correlation between mean monthly current-year June river stage and tree radial growth in southeastern Louisiana. Triangles represent significant positive correlation and crosses represent no significant correlation.

JunH and MayH were significantly correlated with tree radial growth in most of the Atchafalaya Basin sites, but response of tree radial growth to these river stage variables varied in the other two basins (Figures 11 and 12). In the Atchafalaya Basin, the forest stands are mostly flooded by the Atchafalaya River, which contains high nutrient concentrations (Xu, 2006). In addition, the riverine flood waters in this basin may contain high dissolved oxygen (DO) concentrations because DO is high when the water is flowing (Sabo at el., 1999). Therefore, high correlations of May and June river stages with tree radial growth in Atchafalaya Basin sites may be a result of high amounts of nutrients and dissolved oxygen in those sites.

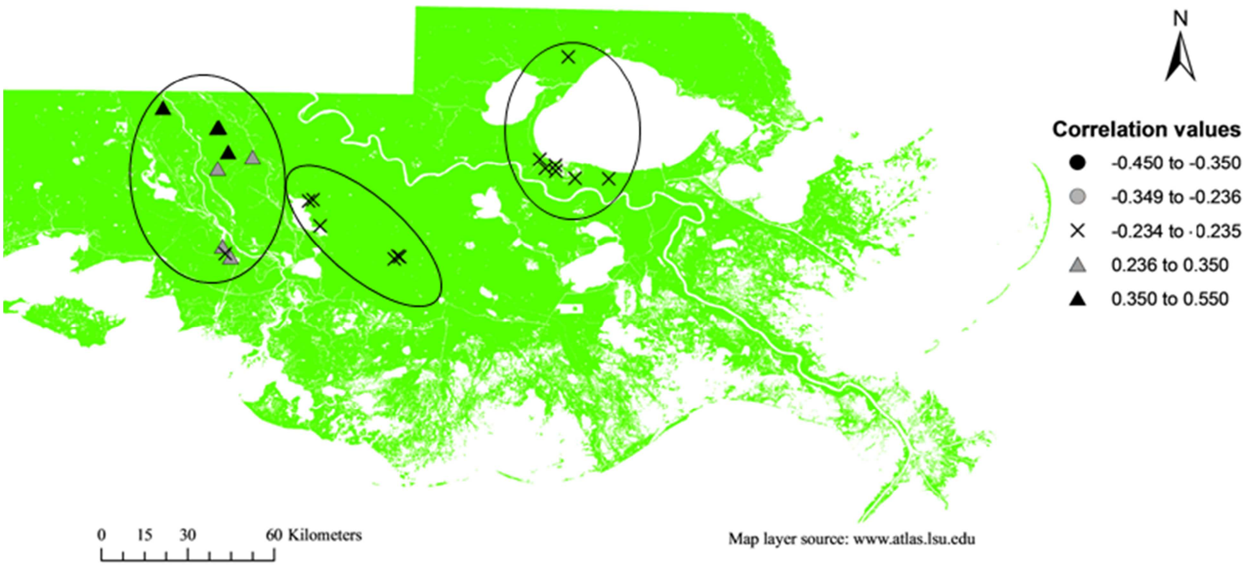

Figure 12: Spatial pattern of correlation between current-year period from July through September river stage and tree radial growth in southeastern Louisiana. Triangles represent significant positive correlation and crosses represent no significant correlation.

The spatial variation may have been caused by site-specific differences in terms of stand dynamics, canopy structure, sediment, nutrient concentration, or edaphic factors pertinent to river stage. A positive correlation between tree radial growth Apr_MayH and JunH variables is consistent with the finding by Cleaveland (2000) who found the highest correlation between total summer flow between1931-1985 and baldcypress tree-ring chronologies from White River in Arkansas. However, explanation of positive correlation between Jan_MarH and tree radial growth is still a question to be investigated. Amos (2006) also found a positive correlation between long-term, riverine flooding and tree radial growth. There was no significant correlation between tree radial growth at most of sites in the Lake Verret Basin and river stage. However, May river stage was positively correlated with tree radial growth at few sites in the Lake Verret Basin. This may be because these sites receive sediment, nutrients, and flowing water from the agricultural runoff from nearby fields via Godchaux Canal (Conner and Day, 1992) at that period of the year.

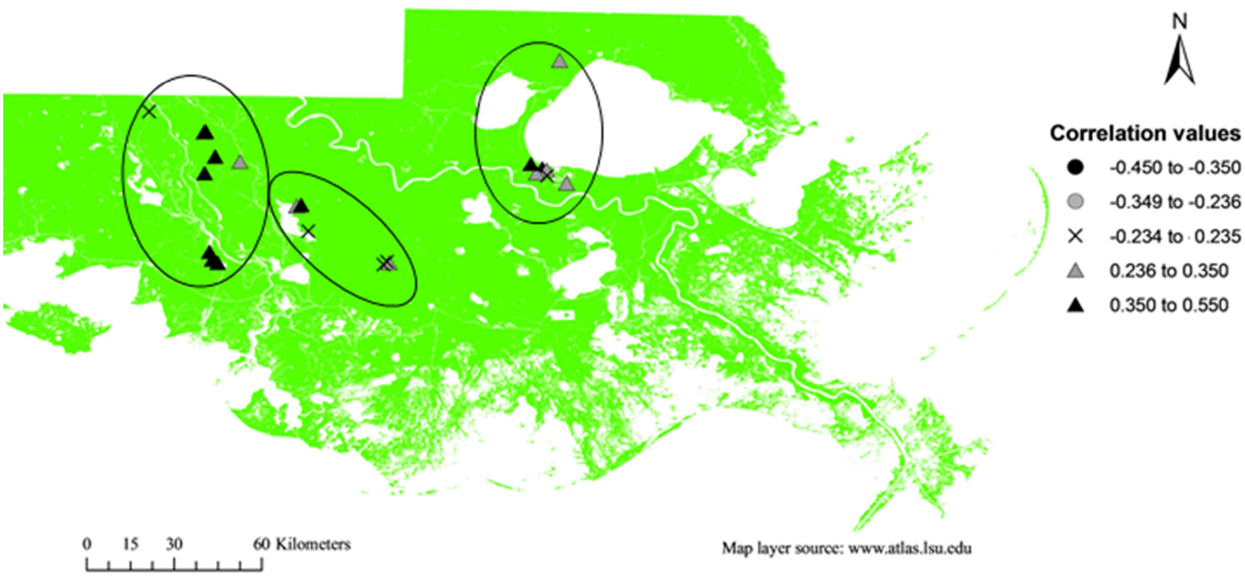

Figure 13: Spatial pattern of correlation between mean monthly current-year May river stage and tree radial growth in southeastern Louisiana. Triangles represent significant positive correlation and crosses represent no significant correlation.

Coastal Water Level and Tree Radial Growth Relationship

Overall, two individual coastal water level variables, namely AprTi and JunTi, had significant positive correlation with tree radial growth (Figure 14). The current-year coastal water level variables had stronger correlation with tree radial growth than previous-year coastal water level variables for most of the sites. But, with multivariate analysis including grouped coastal water level variables, AprMayTi, JunJulTi, PreMarTi, and AugSepTi were positively correlated with cypress radial growth at sites SM, TT, VS (Figure 7). Similarly, Jan_MarTi was strongly positively correlated with cypress radial growth at sites LB and SX. PreNovDecTi was also positively correlated with growth at these sites. At individual sites, there was a positive correlation between PreJulTi and cypress radial growth at the EL, GC, WC, WL, and VU sites.

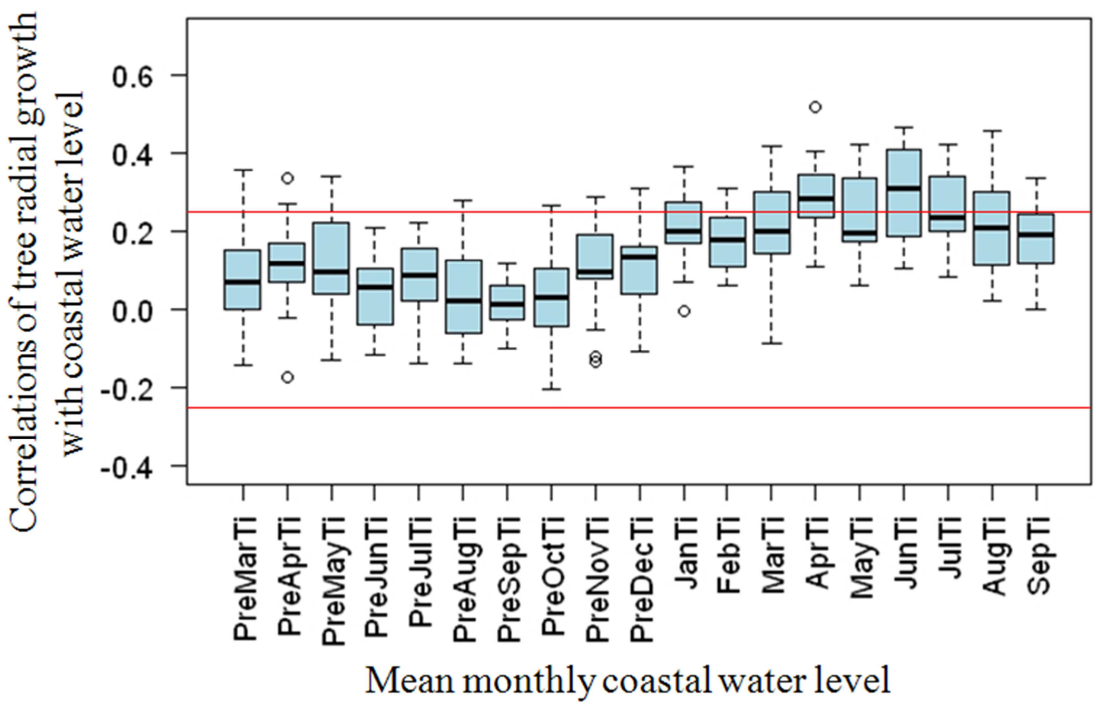

Figure 14: Box and whisker plot of correlations between detrended tree radial growth and mean monthly coastal water level at Grand Isle. The absolute value of correlation below the lower red line or above the upper red line represent the level of statistical significance at $\alpha = 0.05$.

The positive correlation between coastal water level variables (summer period) and tree radial growth in south Louisiana may be explained by the flooding and salinity tolerance nature of baldcypress. However, positive correlation between Jan_MarTi and tree radial growth at sites, LB and SX remains unclear.

MayTi and JunJulTi variables were positively correlated with tree radial growth at most of the sites in the Atchafalaya Basin (Figure 8). However, Jan_MarTi was strongly positive correlated with radial growth at VU in the Atchafalaya Basin. There was variation in the level of radial growth response of trees to Jan_MarTi, MayTi, and JunJulTi water level, but overall, trees in the Lake Pontchartrain and Lake Verret basins responded positively to Jan_MarTi and MayTi (Figures 8, 9, 15, 16, and 17). JunJulTi was positively correlated with tree radial growth at most of the sites in all three basins (Figure 17).

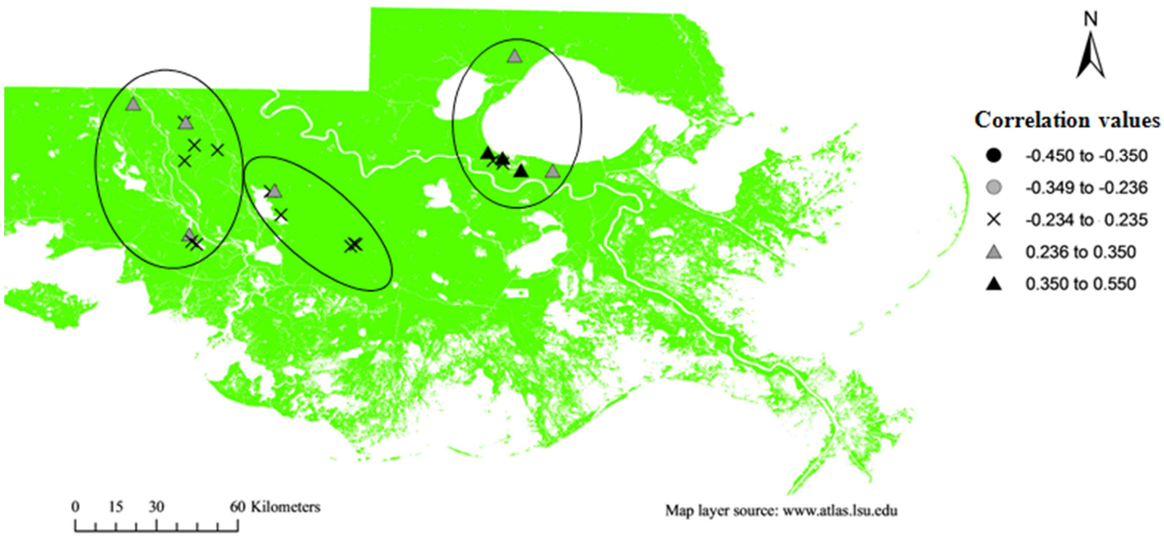

Figure 15: Spatial pattern of correlation between current-year January through March coastal water level and tree radial growth in southeastern Louisiana. Triangles represent significant positive correlation and crosses represent no significant correlation.

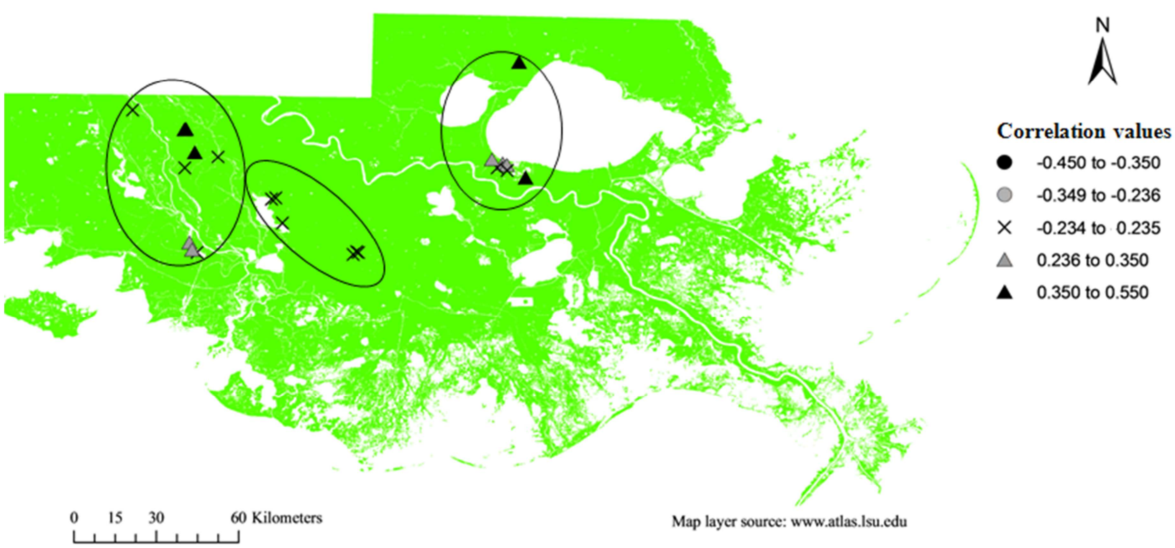

Figure 16: Spatial pattern of correlation between current-year May coastal water level and tree radial growth in southeastern Louisiana. Triangles in the legend represent significant positive correlation and crosses represent no significant correlation.

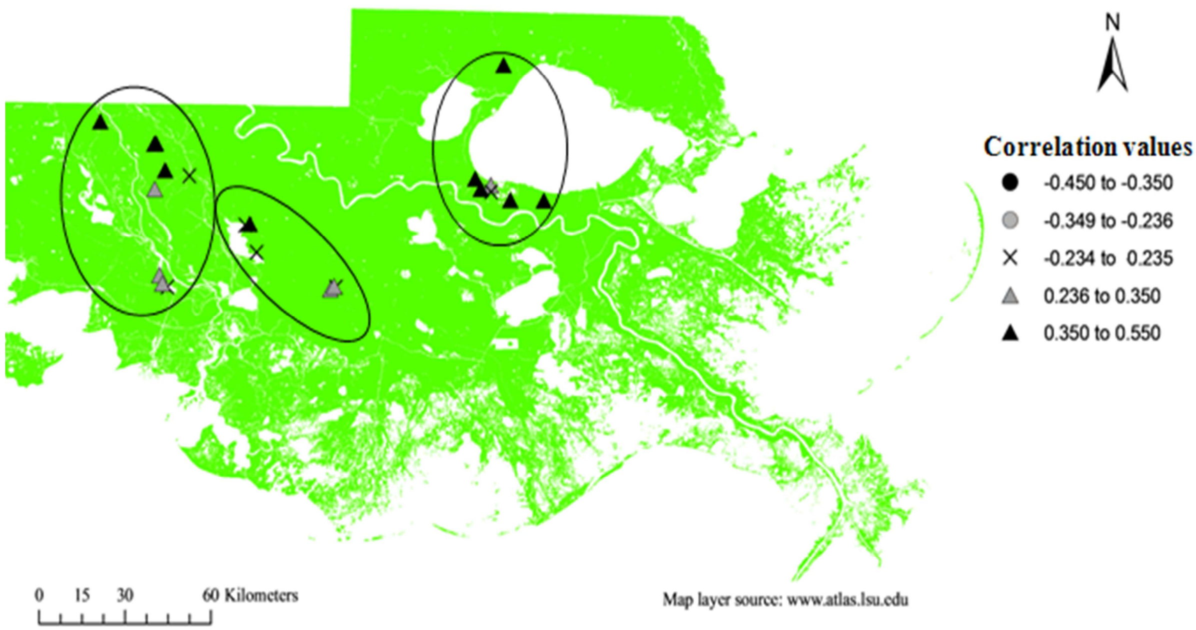

Figure 17: Spatial pattern of correlation between current-year June through July coastal water level and tree radial growth in southeastern Louisiana. Triangles represent significant positive correlation and crosses represent no significant correlation.

Temperature and Tree Radial Growth Relationship

Overall, none of the individual monthly temperature variables had significant correlation with cypress radial growth at any site (Figure 18); but, some of the grouped variables had significant correlation with tree radial growth (Figures 7, 19, and 20).

Based on overall multivariate analysis (Figure 7), PreNov_MarT (mean of all mean monthly temperature variables from previous year's November through current March) was positively correlated with cypress radial growth at sites JBB, TT, VS and SM and PLS, whereas PreAugT was negatively correlated with tree radial growth at these sites. The grouped temperature variables Apr_SepT and PreAprMayT were negatively correlated with cypress radial growth at sites EL, LB, GC, SX, WC, WL, and VU, while PreJunJulT was somewhat positively correlated with these sites with exception of the LB and SX sites. These relationships are consistent with the finding by Reams and Van Deusen (1998) who also noted that overall climate and tree-ring growth had low correlation. At individual sites, a few grouped temperature variables were positively correlated (PreNov_MarT) while others (PreAugT, Apr_SepT, PreAprMayT) were negatively correlated with growth. The positive correlation between PreNov_MarT and tree radial growth could be attributed to physiological stimulation of the root system due to warming effects on water by this period's temperature (Babalola et al., 1968; Kozlowski et al., 1991). The strong negative correlation between Apr_SepT and tree radial growth could be due to increased water vapor deficit at that period of year. Amos (2006) made a similar suggestion.

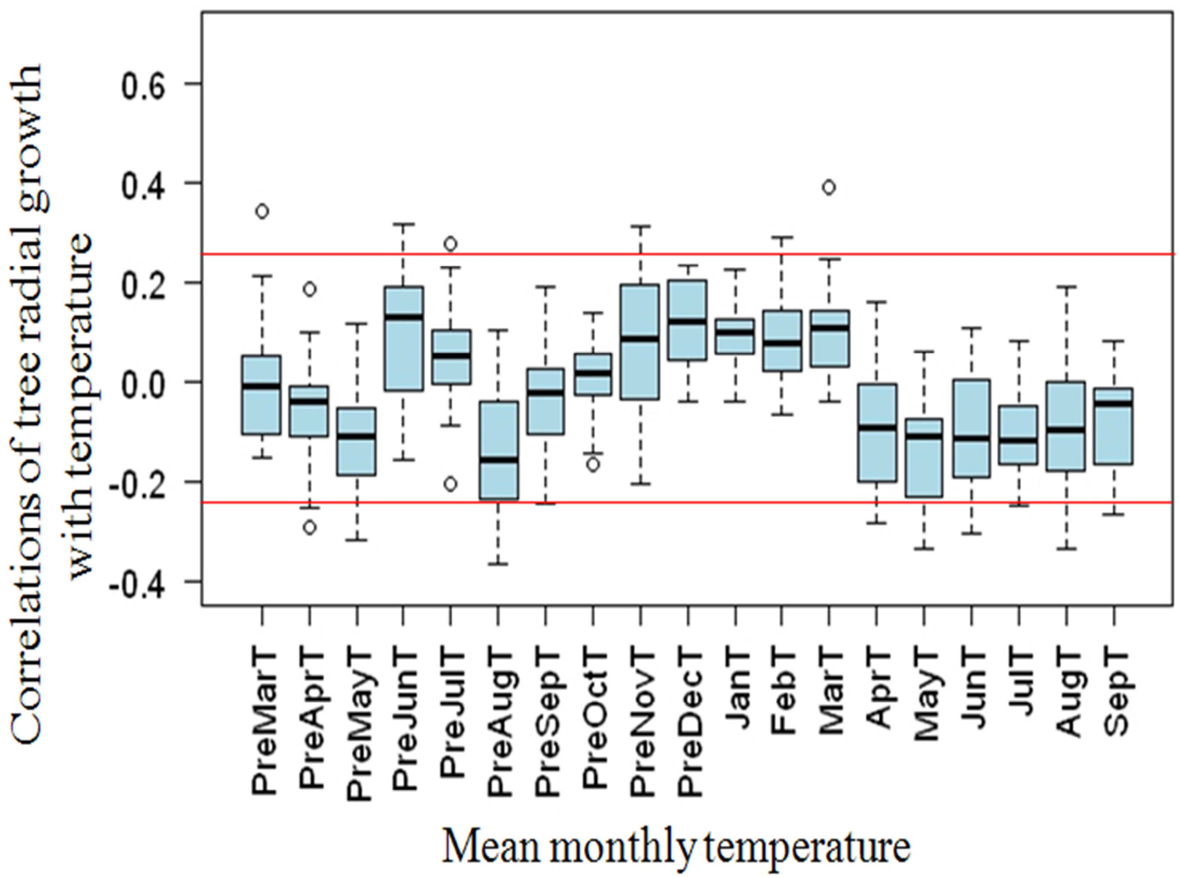

Figure 18: Box and whisker plot of correlations between tree radial growth and mean monthly temperature variables. The absolute value of correlation below the lower red line or above the upper red line represent the level of statistical significance at $\alpha = 0.05$.

The negative correlation between tree growth and previous-year August temperature may be related to the negative effect of temperature on production of stored food reserves, which might have affected the tree radial growth in the following year.

There was a spatial variability in response of the trees to temperature. Overall, temperature was not important for tree radial growth in most of the sites at Atchafalaya Basin (Figures 8, 9, 19, and 20). However, PreJunT was positively correlated with tree radial growth at a few sites in the Lake Pontchartrain and Lake Verret basins (Figures 8 and 19), but not in overall growth (Figure 9).

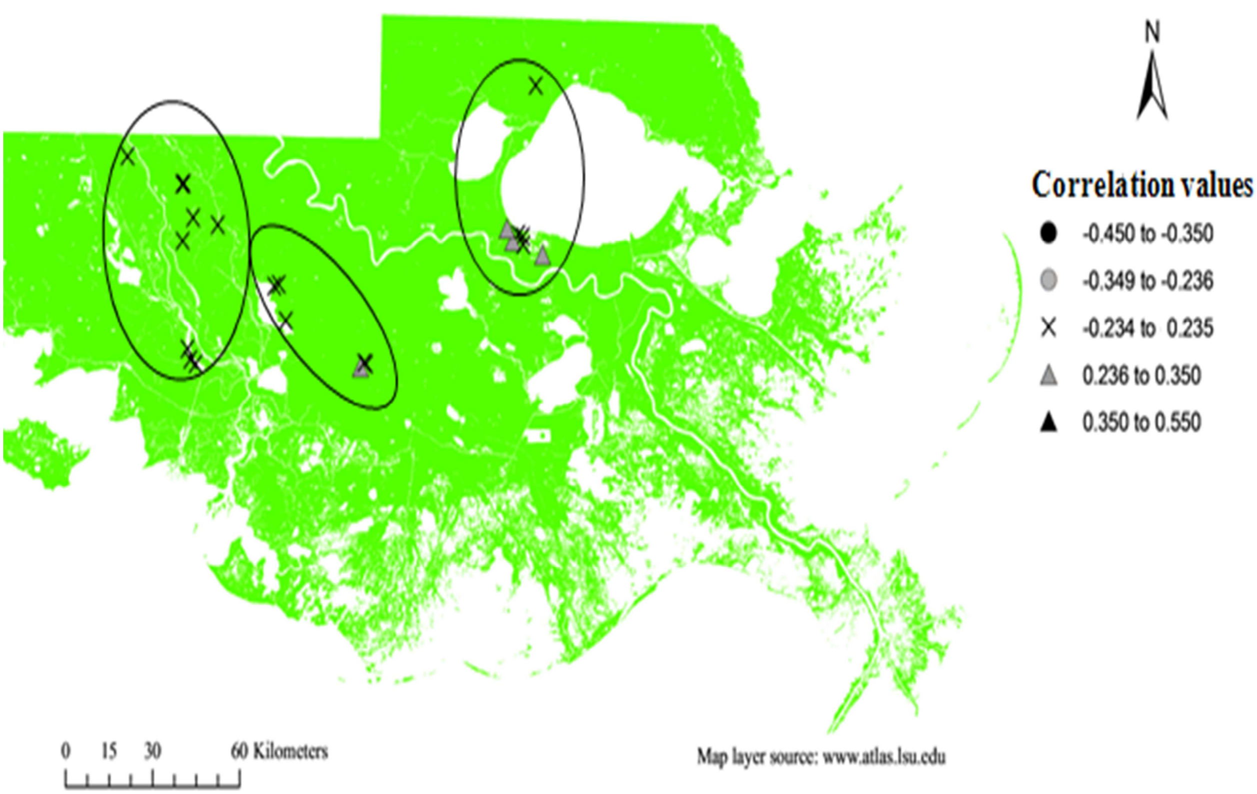

Figure 19: Spatial pattern of correlation between mean monthly previous-year June temperature and tree radial growth in southeastern Louisiana. Triangles represent significant positive correlation and crosses represent no significant correlation.

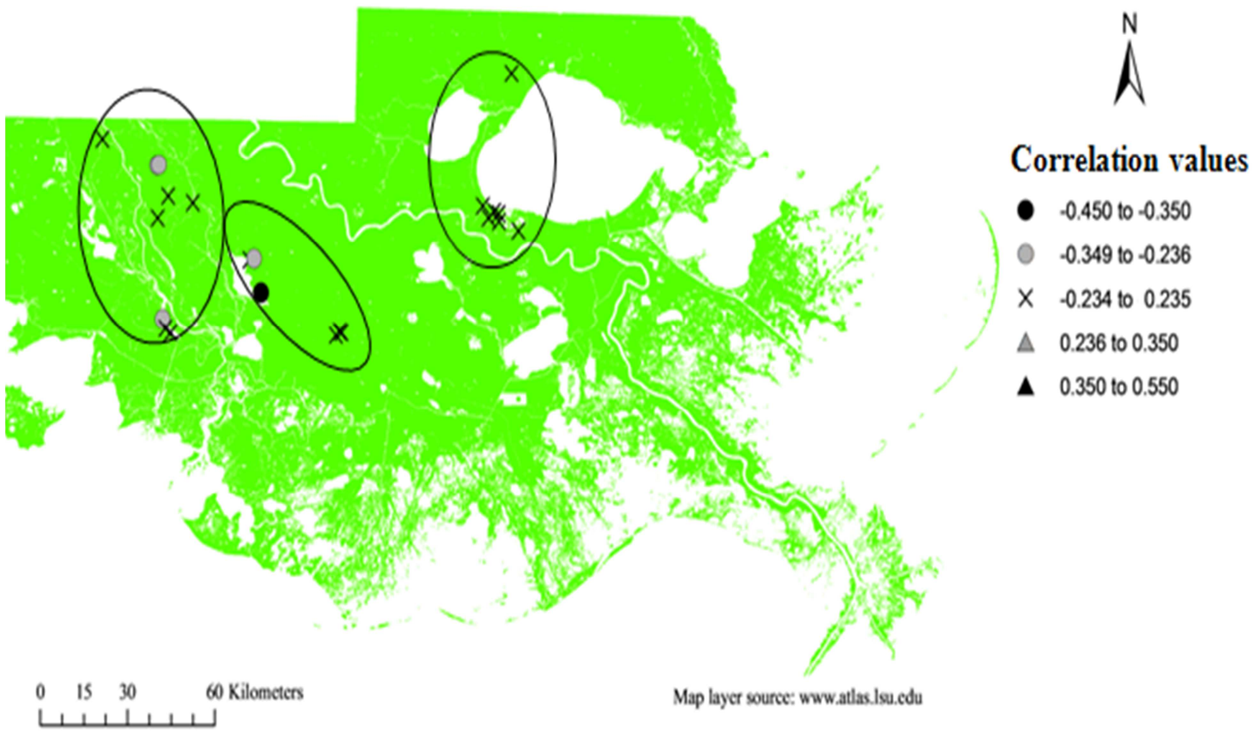

Figure 20: Spatial pattern of correlation between mean monthly previous-year August temperature and tree radial growth in southeastern Louisiana. Circles represent significant negative correlation and crosses represent no significant correlation.

Precipitation and Tree Radial Growth Relationship

Correlations between the twenty-two site chronologies and mean monthly precipitation variable indicated that overall, only MayP had significant positive correlation with overall growth at the sites studied (Figure 21).

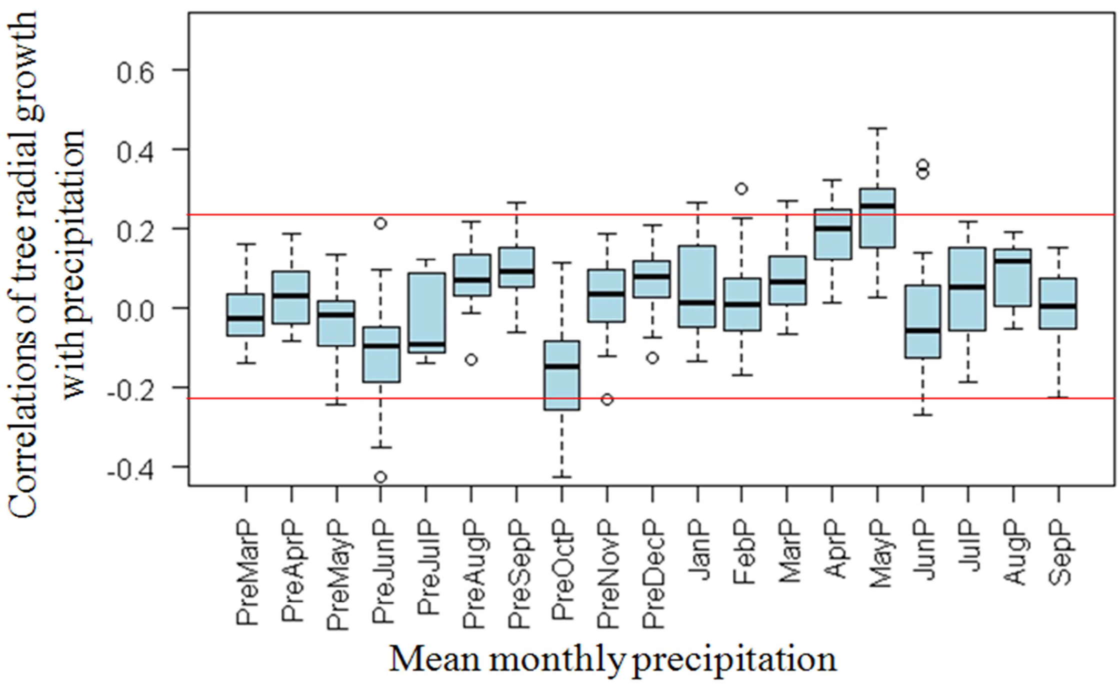

Figure 21: Box and whisker plot of correlations between tree radial growth and mean monthly precipitation variables. The value of correlation below or above the horizontal red lines represent the level of statistical significance at α = 0.05.

While multivariate analysis (Figure 7) indicated that multiple monthly periods of precipitation, such as, AprMayP, PreAugSepP were positively correlated with cypress radial growth at the SM, TT, and VS sites. Jul_SepP was positively correlated with cypress radial growth at the AT, EH, TL, and TO sites. JunP was strongly negatively correlated with growth at the TL site. PreOctP and PreJunP were both strongly negatively correlated with cypress radial growth at the AT, EH, and TO sites. PreJulP had negative correlation with growth at both the TC and LL sites.

Precipitation was not an important variable for tree radial growth in the Atchafalaya Basin except for MayP, which was positively correlated with tree radial growth at the VU site (Figures 8 and 9). When examined separately by site, there was variation in response of trees to MayP, but overall, trees at most of the sites in the Lake Pontchartrain, Lake Verret, and a few sites in Atchafalaya basins responded positively to this variable (Figures 8, 9, and 24). However, overall, PreJunP and PreOctP were negatively correlated with tree radial growth in the Lake Pontchartrain and Lake Verret basins (Figures 9, 22, and 23). The positive correlation between MayP and tree radial growth may possibly be because precipitation at this period helps to reduce water vapor deficit in the air, which reduces water stress on trees (Keim et al., in press), and rainwater also increases dissolved oxygen in flood waters (Davidson et al., 2006). It was unclear why previous-year June and October precipitation were negatively correlated to tree radial growth. Amos (2006) also found similar results for these periods.

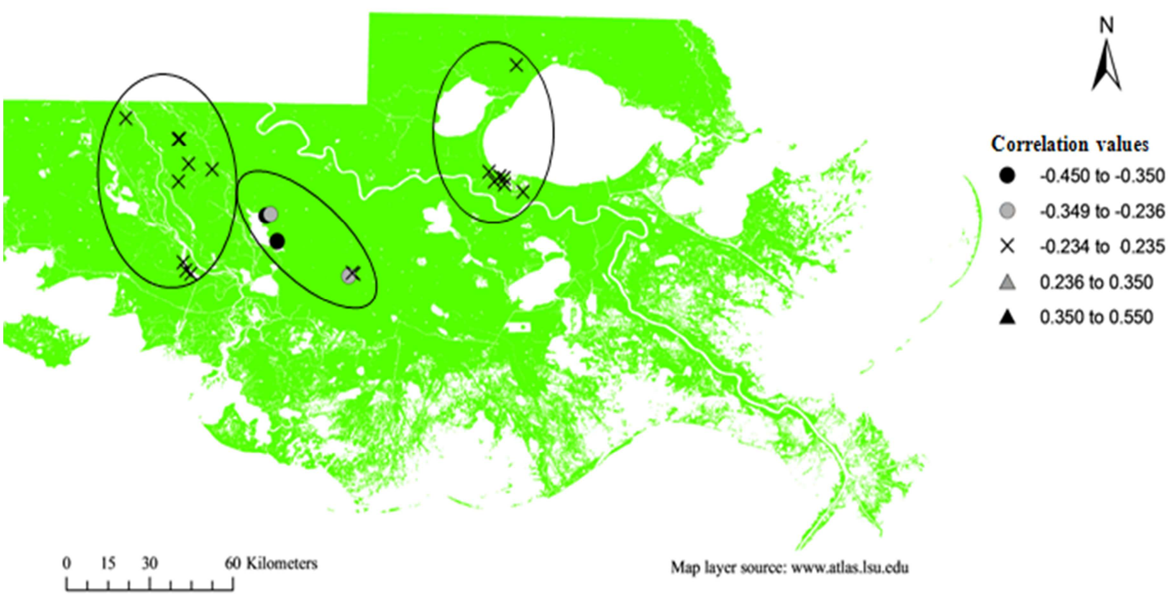

Figure 22: Spatial pattern of correlation between mean monthly previous-year June precipitation and tree radial growth in southeastern Louisiana. Circles represent significant negative correlation and crosses represent no significant correlation.

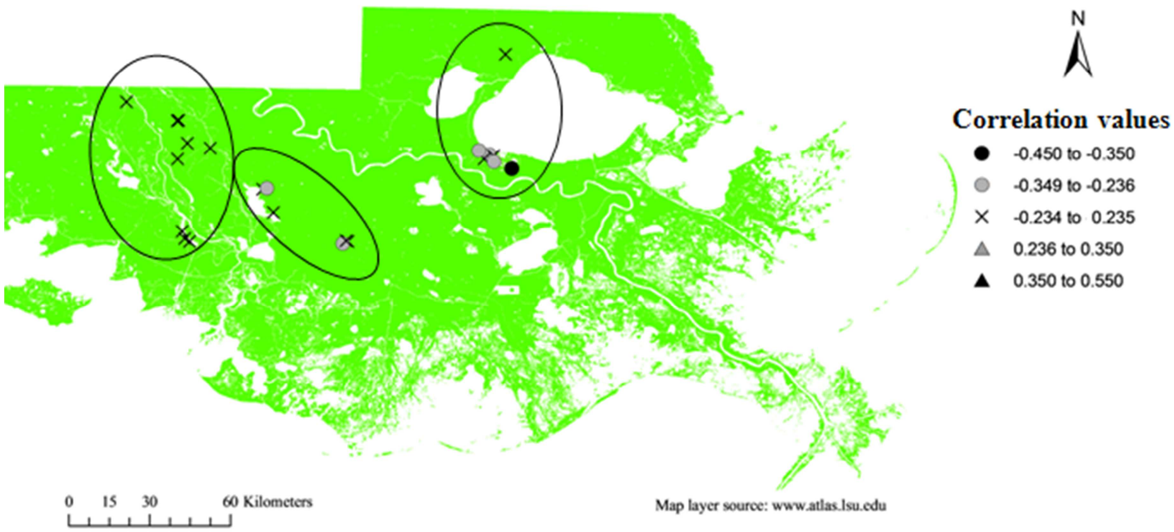

Figure 23: Spatial pattern of correlation between mean monthly previous-year October precipitation and tree radial growth in southeastern Louisiana. Circles represent significant negative correlation and crosses represent no significant correlation.

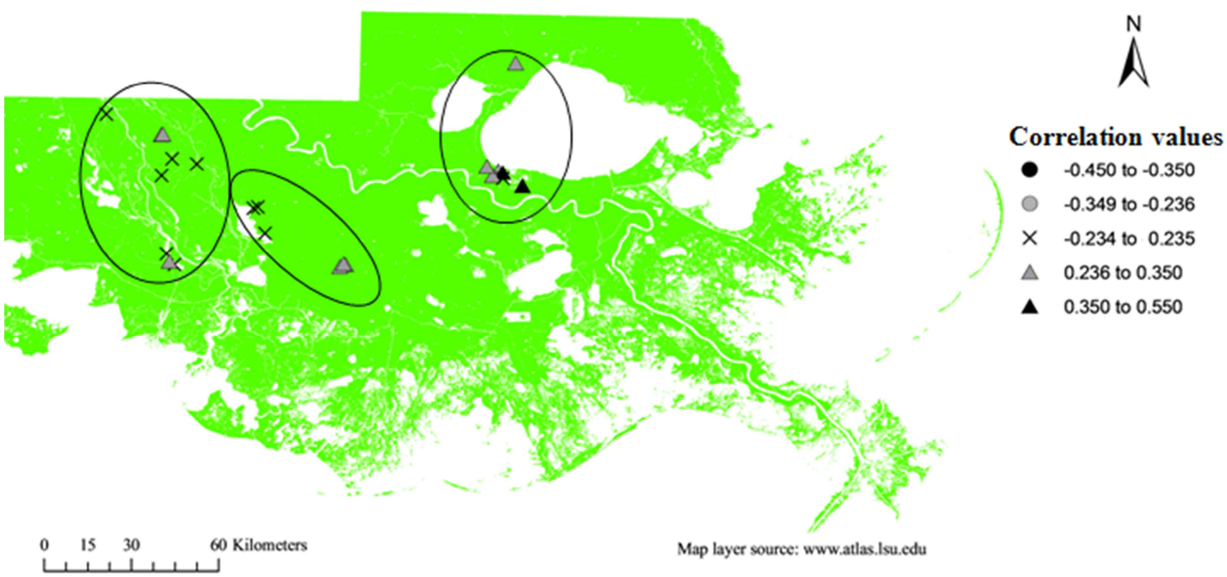

Figure 24: Spatial pattern of correlation between mean monthly current-year May precipitation and tree radial growth in southeastern Louisiana. Triangles represent significant positive correlation and crosses represent no significant correlation.

Because tree radial growth ceases or nearly ceases after September, the strong negative correlation between PreOctP and tree radial growth made sense. However, AprMayP was positively correlated with cypress radial growth at the SM, TT, and VS sites, indicating greater availability of moisture in these sites at those periods and also in Jul_SepP period at AT, EH, TL, and TO sites. Stahle and Cleaveland (1992; 1994) reconstructed spring rainfall of southeastern United States (South Carolina, North Carolina and Georgia) over the past 1000 years using baldcypress tree-rings. They also found a positive correlation between baldcypress tree radial growth and spring rainfall (March to June).

PDSI and Tree Radial Growth Relationship

Correlation of 19 mean monthly PDSI variables across all sites indicated that none of the individual monthly PDSI variables had strong correlations with tree radial growth (Figure 25). However, grouped variables, especially spring PDSI variables, had higher correlation with tree radial growth (Figures 7 and 26).

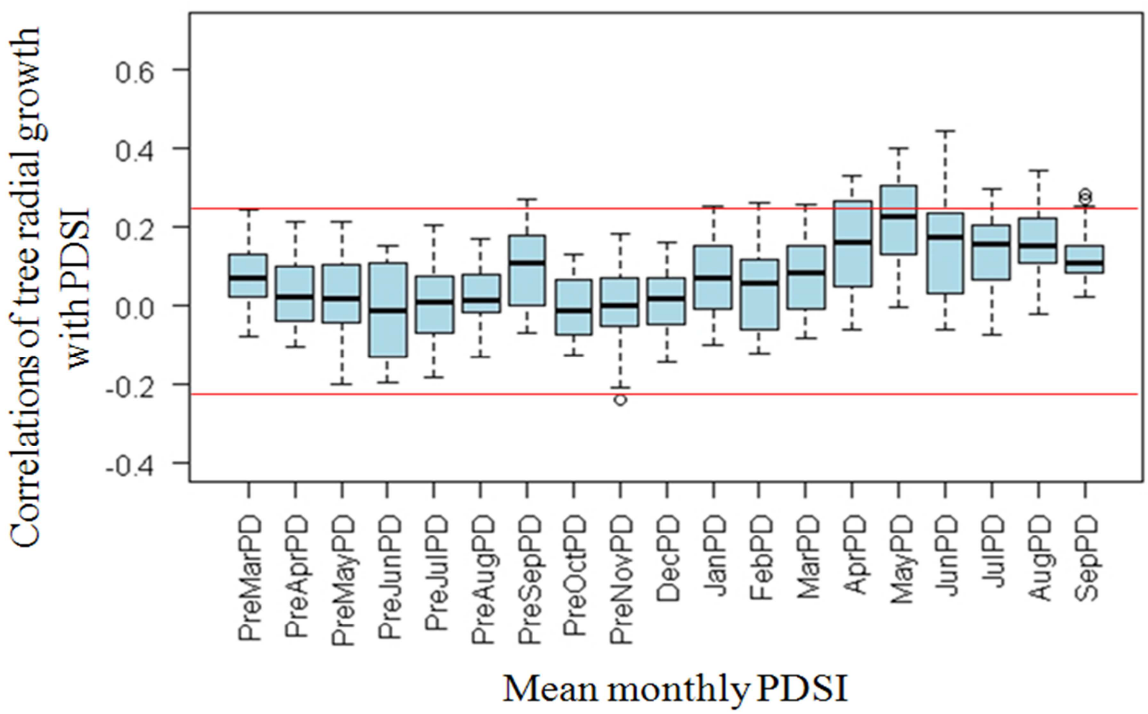

Figure 25: Box and whisker plot of correlations between detrended tree radial growth and mean monthly PDSI variables The absolute value of correlation below the lower red line or above the upper red line represent the level of statistical significance at α = 0.05.

Stahle et al. (1988) in southeastern North Carolina and Georgia, and Reams and Van Deusen (1998) also found that June PDSI was positively correlated with baldcypress ring chronologies in Louisiana. There was a significant correlation between tree radial growth on most of the sites in the Lake Pontchartrain Basin and Apr_JunPD PDSI variable (Figure 26).

In general, the PDSI and PHDI calculation is a linear combination of several variables. So, there is always a greater probability of these variables causing a problem of multicollinearity in regression. PDSI had high multicollinearity with other mean monthly variables and was, therefore, removed from the multivariate independent data set used in redundancy analysis (Table 10).

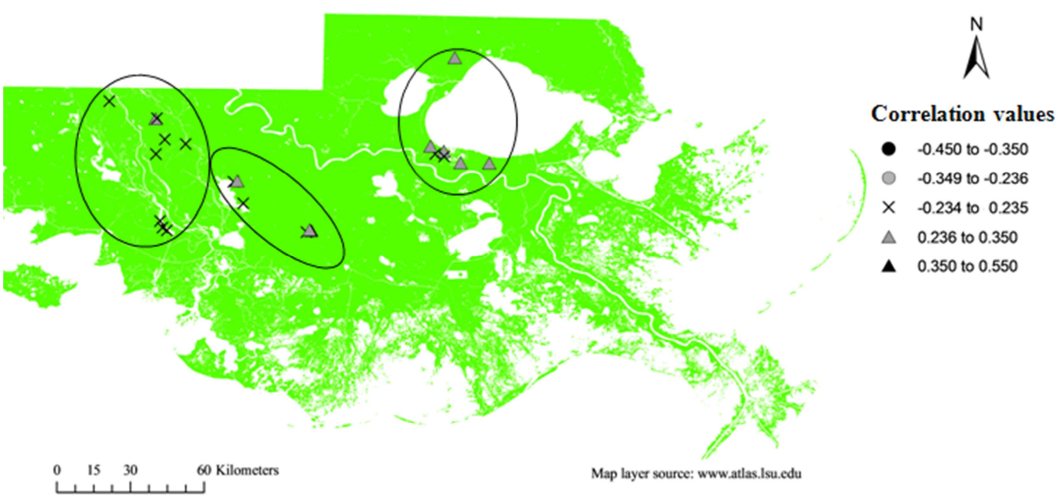

Figure 26: Spatial pattern of correlation between current-year period from April through June PDSI and tree radial growth in southeastern Louisiana. Triangles represent significant positive correlation and crosses represent no significant correlation.

PHDI and Tree Radial Growth Relationship

Overall, none of individual monthly PHDI variables had strong correlations with tree-radial growth (Figure 27). However, for the multivariate analysis of grouped variables (Figure 7), only May_SepPH remained in the model, and was strongly positively correlated with tree radial growth at the SM, TT, and VS sites. PDSI and PHDI behaved in a similar way since these two are closely related variables. For most of the sites in the Lake Pontchartrain Basin and a few in the Lake Verret Basin, tree radial growth was positively correlated with May_SepPH (Figure 28).

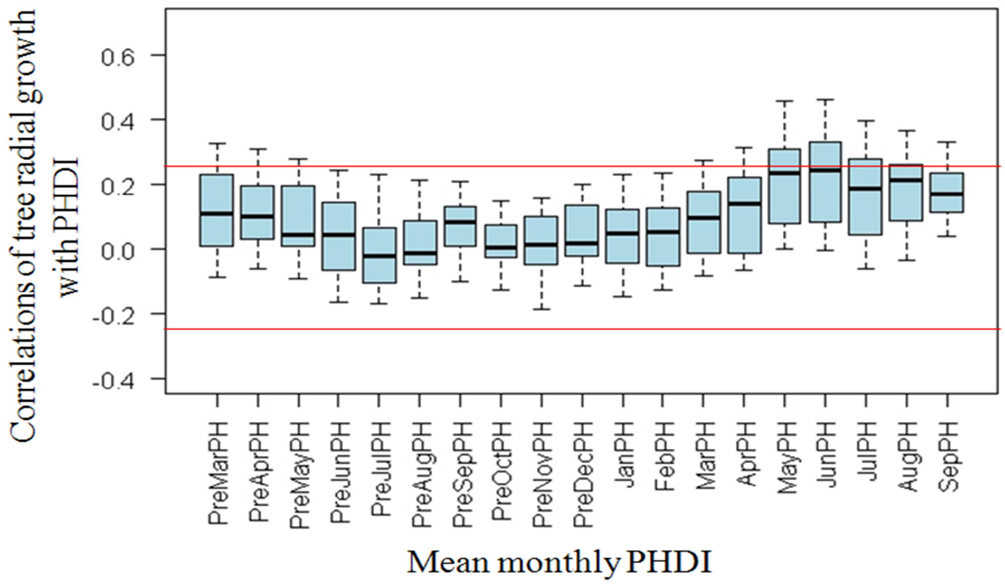

Figure 27: Box and whisker plot of correlations between detrended tree radial growth and mean monthly PHDI variables. The value of correlation below or above the horizontal red lines represent the level of statistical significance at α = 0.05.

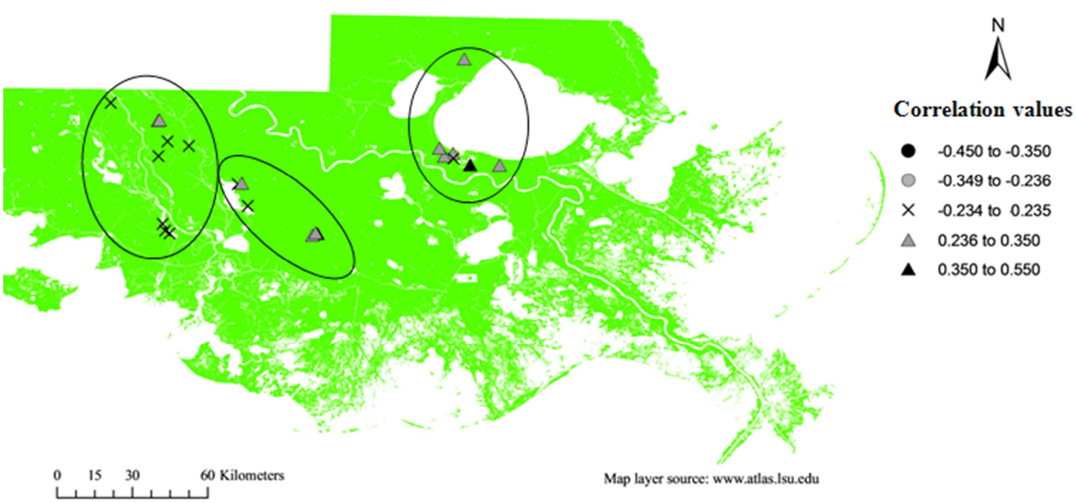

Figure 28: Spatial pattern of correlation between current-year May through September PHDI and tree radial growth in southeastern Louisiana. Triangles represent significant positive correlation and crosses represent no significant correlation.

River Stage and Coastal Water Level Relationship

One of the most interesting findings of this study was that coastal water level and river stage were highly correlated (Figure 29). In addition, forests responded to coastal water level and river stage in a very similar manner and during the same time periods. It was especially surprising that coastal water level variables were correlated with growth in places where no tidal action occurs (for examples, LL, PLS, BCL). It may be inferred that the river stage is influencing the coastal water level in the spring when flow is high. Therefore, the consequence to forests due to river stage is further intensified by the coastal water level parameters in this system especially at those sites with coastal influence. A strong relationship between the coastal water level and river stage suggests that river stage often controls coastal water levels, so that even sites not directly hydrologically connected to the rivers experience the broad-scale effects of annual variability in river stage because of the possible effect of backwater flooding.

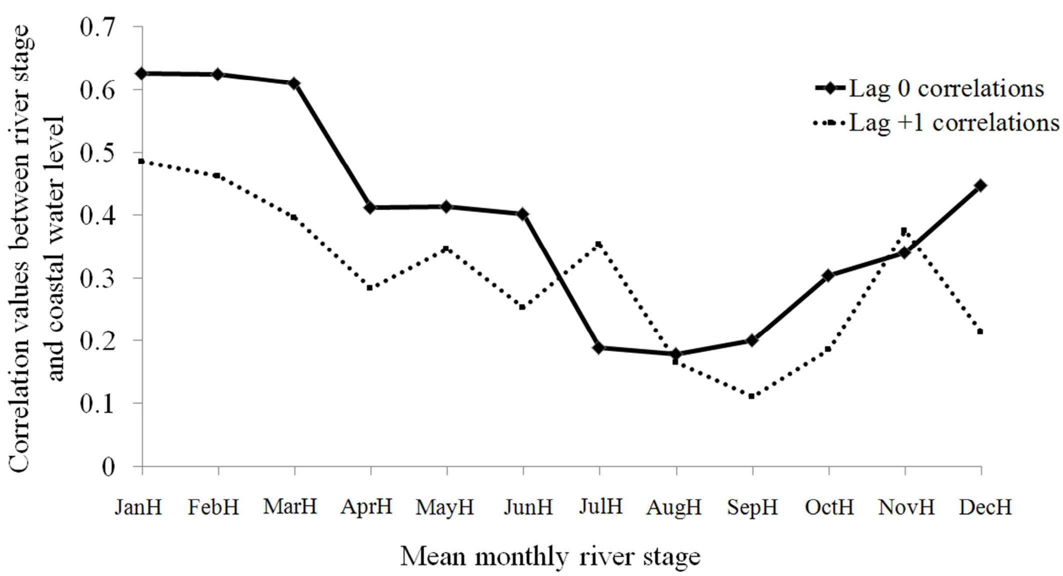

Figure 29: The simple correlations between previous year's monthly stage data from Mississippi River and detrended coastal water level data (representing mean sea level) from Grand Isle, Louisiana. The solid black line (lag 0) represents correlations between same monthly river stages with the same monthly coastal water level and the dotted line (lag +1) represents the correlations between monthly river stages with the following monthly coastal water level.

General Discussion of Results from This Study in Relation to Other Comparable Studies

A few studies have directly looked into the responses of baldcypress radial growth in relation to climatic and hydrological variables in various settings. In this study, baldcypress radial growth was found to be significantly, positively correlated with hydrological variables (both river stage and coastal water level) compared to other climatic variables. In this study, it was found that the baldcypress radial growth was positively correlated with current year May and June river stage, which is consistent with the findings by Rypel et al. (2009). Cleaveland (2000) also found the highest correlation between total summer flow for the period of 1931-1985 and baldcypress tree-ring chronologies from White River in Arkansas. In the productivity and dendrochronological analysis of coastal swamp forests in Louisiana in relation to climate and hydrology, Keim and Amos (in press) also found that hydrology was the dominant factor over climate for baldcypress radial growth. The result of this study concerning effects of hydrology on baldcypress growth was also consistent with the finding by Doyle et al. (2007). They, in the study of baldcypress growth in the tidal freshwater swamps of a coastal riverine system in South Carolina, found that high river flow for sustained periods might lower salinities in the forest soils and, thus help increase tree growth.

Overall, it was found that climate had low correlation with baldcypress radial growth as compared to that of hydrology. These relationships are consistent with the finding by Reams and Van Deusen (1998), who also noted that overall climate and tree-ring growth in the southern Louisiana had a lower correlation than elsewhere. Keim and Amos (in press) also found a similar result. As an individual monthly precipitation variable included in this study, May precipitation was positively correlated with baldcypress radial growth. Similarly, other studies found the spring precipitation (Stahle and Cleveland, 1992; 1994; Keim and Amos, in press) was positively correlated with baldcypress radial growth. Similar to Stahle et al. (1988) and Reams and Van Deusen (1998), this study found that April through June PDSI was positively correlated with baldcypress tree growth.

In this study, I found a pattern of high correlation between river stage and coastal water level, and thus concluded that river stage influences coastal water level when the flow is high. However, Doyle et al. (2007) found uncorrelated patterns of river flow and tide stages. This contrasting result may be due to variability in estuaries. Doyle et al. (2007) studied a small river where riverflow is comparatively low and uncorrelated patterns occur because exchange with the ocean is greater than river influence on the estuary.

The results from this study showed an interconnection in the relationships between river stage and coastal water coastal in relation to baldcypress radial growth. Though there are other factors that affect coastal wetland forest productivity in this system, hydrology seems to be the most positively correlated component with tree radial growth. Thus, in spite of other components of ecosystems that control the productivity of deltaic wetlands forests, the gross measurement of hydrology (river stage and coastal water level) is significantly associated with tree radial growth of coastal wetland forests.

In most of the studies related to tree growth and climate and hydrology, the relationship is assumed linear, which is not always the case (Fritts, 1976). More work can be done to extract signals using nonlinear relationships or more complex analytical techniques to determine more detailed eco-hydrologic relationships. For example, Zhang et al. (2000) used artificial neural network to explore the relationship between tree growth and climate.

CONCLUSIONS

River stage and coastal water level variables were mostly positively correlated with cypress radial growth. Overall, broad-scale measures of deltaic hydrology (river stage and coastal water level) had higher correlations with tree radial growth than did climatic variables.

Tree radial growth responses to hydrology (both river stage and coastal water level) and climate varied spatially by individual sites and basins. Basin-level effects are probably related to hydrological and biogeochemical processes that vary by basin.

A strong relationship between coastal water level and river stage suggests that river stage controls (influences) coastal water levels at some times of the year, so that even sites not directly hydrologically connected to the river experience the broad-scale effects of annual variability in river stage.

Therefore, even though the river is leveed, river hydrology appears to influence forest productivity through linkages with coastal waters.

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APPENDIX A: SITES, CODES, FIELD SAMPLER AND LAB PROCESSOR OF THE DATA SOURCES USED IN THIS STUDY

Site Name	Code	Field Sampler	Lab Processor[1]
Attakapas	AT	2, 1	2
Bayou Cowan Low-flow	BCL	1, 18	1, 4, 5
Bayou Pigeon	BP	1, 15, 18, 13	1, 4, 5, 3
Bee Bayou Low-flow	BBL	1, 15	4, 1, 3, 5, 8
Berry Lake or BLC	BLBLC	1, 24, 16	9, 3
Elm Hall	EH	2, 1, 20, 22	2
Bonnet Carré East Levee	EL	1and his crew	1
Godchaux Canal	GC	2, 13	2
Joyce WMA Black Bayou	JBB	10, 19, 1, 14	10
LaBranche	LB	1and his crew	1
Long Lake	LL	1, 14, 9, 21	8, 1, 3
Pierce Lake South	PLS	1, 9, 24, 16	9, 11, 3, 12
Six Mile North	SM	2, 1, 25, 22	2
Bonnet Carré Suxion Canal	SX	1and his crew	1
Thibodaux Control	TC	6, 6, 1, 13, 2, 7	6, 6, 7, 1
Bayous Traverse and LaBranche	TL	1 and his crew	1
Thibodaux Outflow	TO	6, 6, 1, 13, 2, 7	6, 6, 7, 1
Thibodaux Treatment	TT	6, 6, 1, 13, 2, 7	6, 6, 7, 1
Verdunville	VU	2, 23	2
Verdunville South / Grayhorse Island	VS	2, 13	2
LaBranche Walker Canal	WC	1and his crew	1
Bonnet Carré West Levee	WL	1and his crew	1, 2

[1] 1= Keim, 2= Amos, 3=Bohora, 4= Margo, 5=DeGravelles, 6=Hartman, 7= Izdepski, 8=Hutchinson, 9=Scaroni, 10=Shah, 11=Bowen, 12=Hsueh, 13=Zoller, 14=Newman, 15=Nyman, 16=High School Students, 18=Constant, 19=Chambers, 20=King, 21=Tobias, 22= Devisscher, 23=Dimov, 24=Orr, 25= Doyle. The numbering here does not necessarily mean the individual's ranking.

APPENDIX B: SITES, SAMPLING DATES, LATITUDE/LONGITUDE FORMS OF GPS COORDINATES OF THE LOCATIONS

Site Name	Code	Sampling Dates	Latitude	Longitude
Attakapas	AT	04/02/2005	29.8543	91.0995
Bayou Cowan Low-flow	BCL	07/06/2006, 10/11/2006	30.0327	91.4195
Bayou Pigeon	BP	05/05/2006, 07/06/2006	30.0693	91.3112
Bee Bayou Low-flow	BBL	28/07/2006, 10/11/2006	30.0858	91.3865
Berry Lake or BLC	BLBLC	07/12/2007	30.1607	91.4202
Elm Hall	EH	17/07/2005	29.9313	91.1355
Bonnet Carré East Levee	EL	27/01/2009	30.0484	90.3788
Godchaux Canal	GC	09/08/2005	29.9357	91.1222
Joyce WMA Black Bayou	JBB	30/03/2007	30.3819	90.3249
LaBranche	LB	27/01/2009	30.0424	90.3655
Long Lake	LL	02/02/2007	30.2225	91.5905
Pierce Lake South	PLS	30/11/2007	30.1622	91.4153
Six Mile North	SM	26/07/2005	29.7903	91.4047
Bonnet Carré Suxion Canal	SX	27/01/2009	30.0328	90.3966
Thibodaux Control	TC	30/12/2005	29.7564	90.8513
Bayous Traverse and LaBranche	TL	27/01/2009	30.0246	90.3640
Thibodaux Outflow	TO	30/12/2005, 31/03/2006	29.7512	90.8687
Thibodaux Treatment	TT	13/11/2005, 31/03/2006	29.7588	90.8574
Verdunville	VU	24/01/2005	29.7667	91.3957
Verdunville South / Grayhorse	VS	01/08/2005	29.7563	91.3795
LaBranche Walker Canal	WC	27/01/2009	30.0022	90.3034
LaBranche West Levee	WL	27/01/2009	30.0612	90.414

VITA

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